THE LOWER TAYLOR GROUP:

Taylor and Wright Valleys, southern Victoria Land, Antarctica;

Paleoenvironmental Interpretations and Sequence Stratigraphy

A thesis submitted in partial fulfilment of the requirements for the Degree

of Master of Science in Geology

at the University of Canterbury

by Mr Timothy F. O'Toole

University of Canterbury

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For Jerry

Acknowledgments

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Thank you to my supervisor Kari Bassett, especially for keeping my ramblings on the right track and providing your honest opinions throughout. Thank you also for your constant encouragement and reinforcement

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Lastly, I would like to dedicate this thesis to a family member that we recently lost, Jeremy (Jerry, Jem). I cannot thank you enough for all of you help and support and knowledge throughout my education. Your support and role in our family will never be forgotten.

Abstract

The Devonian Taylor Group (the lower Beacon Supergroup), in the Taylor and Wright Valleys, southern Victoria Land (SVL), Antarctica, is separated from basement by a regional nonconformity, the Kukri Erosion Surface. Thereafter the Taylor Group sediments, observed in this thesis, are affected by two localized unconformities; the Windy Gully Erosion Surface, separating the Terra Cotta Siltstone Formation (TCzst) and older units from the younger overlying New Mountain Sandstone; and the Heimdall Erosion Surface (HES), separating the New Mountain Sandstone Formation (NMSst) and older units from the overlying Altar Mountain Formation. The depositional environments of the Windy Gully Sandstone, New Mountain Sandstone and Altar Mountain Formations have long been under debate.

The Kukri Erosion Surface (KES) truncates the crystalline basement and separates the basement rock from the overlying Beacon Supergroup. Interpretation of the erosion surface characteristics and the directly overlying basal conglomerate lithofacies (WG-BCL) suggest a high relief rocky shore platform environment during a sustained and significant relative sea level fall. The environment has been suggested to be similar to what is currently seen on the West Coast, New Zealand today.

The Windy Gully Sandstone Formation directly overlies the KES and consists of a basal conglomerate (WG-BCL) followed by moderately to well sorted tabular and trough cross bedded felds- to subfeldsarenites. At one location an interbedded siltstone and cross bedded sandstone lithofacies was observed and interpreted as a tidal flat. Overall interpretation of the WGSst suggests continued progradation from a rocky shore platform (WG-BCL) to a series low angle beach, to shallow marine, and back to low angle beach environments. This occurred during a relative sea level rise. Shallowing of the water column produced a gradational relationship with the Terra Cotta Siltstone Formation (TCzst).. The fine to very fine sandy mottled, well laminated siltstones moving to very fine fissile dark siltstones suggest a progression from sandy estuarine to a mud flat environment. The Terra Cotta Siltsone is truncated by the Windy Gully Erosion Surface

The Windy Gully Erosion Surface is observed in the Handsley Valley by the presence of TCzst rip-up clasts in the directly overlying New Mountain Sandstone Formation. Elsewhere the horizon is either very sharp or has desiccation cracks present suggesting a cessation of deposition and subaerial exposure respectively. This suggests a small relative fall in sea level with only localized erosion.

The New Mountain Sandstone Formation (NMSst) predominantly consists of a series of low angle tabular and higher angle trough cross beds. It has a subfeldsarenite base that progressively becomes a pure quartz arenites. Interpretation suggests an initial beach environment with rejuvenated sediments moving to quartzose shallow marine and back to beach environments. This represents a relative sea level rise with continued progradation

The NMSst is truncated in the north by the HES forming a characteristic saw tooth pattern in the cross bedded sandstones; elsewhere the HES is represented by a feldspathic influx moving into the Altar Mountain Formation. The HES was formed due to a significant relative sea level fall leading to exposure and erosion of lithified NMSst cross beds in the north but continuation of deposition in the south.

The Altar Mountain Formation consists of tabular and trough cross bedded subfields- to feldsarenites. The Odin Arkose Member directly overlying the HES is a granule to cobble conglomerate in the north where the HES is erosional and very coarse sand to granule feldsarenite in the south where the HES is conformable. This has been interpreted as a pebbly shore platform to coarse sandy to granular beach environment. The following Altar Mountain Formation is interpreted as a continuation of medium to coarse sandy beach environments with influxes of coarser sediments and possibly moving into shallow marine in places.

Sequence stratigraphy identifies three stratigraphic sequences: S1, the Windy Gully Sandstone and Terra Cotta Siltstone Formations; S2, the New Mountain Sandstone Formation; and S3, the Altar Mountain Formation. The first two sequences (S1&S2) show a clear progression through transgression to a high stand systems tract through regression to a low stand systems tract. The Altar Mountain Formation follows a very similar trend but due to the lack of time and data the above measures have been speculated.

Zircon age dating suggests the source of the sediments in the area come from the Neoproterozic Skelton Group and the DV2a Granite Harbour Intrusives, both directly underlying the sandstones but are exposed elsewhere in SVL. Laminated sandstone clasts within the New Mountain Basal Conglomerate Lithofacies (NM-BCL) are suggested to be sourced from recycled sediments directly below. Other exotic clasts are also observed in the lithofacies are of unknown origin.

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ii. Glossary

GENERAL

Adobe Illustrator 9.0.1 – Primary software for the construction of stratigraphic columns

Grapher 7 – Graphing software; used to plot Rose diagrams for paleocurrent trends and direction

GPS – Global Positioning System; used to locate position in the field and, in particular, location and tracking along the measured stratigraphic section

Rose diagrams – plot paleocurrent data by dip and dip direction thus showing any trends of paleoflow direction

SVL – Southern Victoria Land

Geological Units (in stratigraphic order, base to top)

HES – Heimdall Erosion Surface; the primary erosion surface for this research, located between the lower New Mountain Sandstone Member and the above Odin Arkose Member

NMSst – New Mountain Sandstone

TCzst –Terra Cotta Siltstone

WGSst – Windy Gully Sandstone

KES – Kukri Erosion Surface; the basal nonconformity in Southern Victoria Land

1. Chapter 1- Introduction

The paleoenvironment of some of the lower formations in the Taylor group are uncertain and have been much debated whilst the formation of the Heimdall Erosion Surface is not well understood. The depositional environment of the New Mountain and Windy Gully Sandstone Formations are an especially contentious issue due to their interpretations depending on the particular type of research undertaken and their physical similarity and therefore comparison of each other. Investigation of the Heimdall Erosion Surface has been undertaken by fellow University of Canterbury post graduates; (Savage, 2005; Gilmer 2008) but not previous conclusions have been made as to how it formed or how it changes paleoenvironmental conditions above and below.

The primary aim of this research is to determine the mechanisms that formed the Heimdall Erosion Surface. This includes interpretation of the depositional environment of the lower Taylor Group sediments in the Wright and Taylor Valleys including the basal erosion surface, the Kukri Erosion Surface, and the following formations (the Windy gully Sandstone, the Terra Cotta Siltstone and the New Mountain Sandstone Formations) up to the Altar Mountain Formation. The research uses a variety of methods to resolve the interpretation issues of the Taylor sediments including facies interpretation, sedimentary structures and trace fossils. In addition, provenance analysis of the sandstones by means of detrital zircon U-Pb dating will determine any changes in the source rock over the Heimdall Erosion Surface and sequence stratigraphy will be used to show the progression of environmental conditions and determine particular sequence tracts and progression thereafter.

Overall, this research provides a more detailed analysis of the lower Taylor sediments in particular the lateral changes of the Heimdall Erosion Surface and other particular horizons below.

Summary of research aims:

- Determination of the depositional settings of the Windy Gully Sandstone, Terra Cotta Siltstone, New Mountain Sandstone and Altar Mountain Formations
- Understand the mechanisms that lead to the formation of the Heimdall Erosion Surface and other erosional surfaces below (the basal Kukri Erosion Surface and debated Windy Gully Erosion Surface)
- Identify the provenance of the Windy Gully and New Mountain Sandstone and Altar Mountain Formations, including the Odin Arkose Member
- Construct a sequence stratigraphy progression for the lower Taylor Group sediments

- Determine the depositional settings throughout the deposition of the lower Taylor Group Sediments

1.1 Field Areas

The area of interest for this study is concentrated in Southern Victoria Land starting at Mt Boreas (S77° 29.782') (Wright Valley) and moving as far South as Rotunda (S78° 01.696') (south of the Ferrar Glacier). Throughout our time in the field we camped at 6 different sites, gradually moving south observing the lateral change in the HES. Field sites were chosen based on previous work in the area by Barrett and Webb (1973) and Plume (1976, 1978, 1982) and where the HES and the Taylor sediments were accessible. The Field sites are located as follows: Figure 1.1

- Mt Boreas (S77° 29.782' , E161°13.769') – 1496m
- Nibelungen Valley (S77° 35.778' , E161° 23.628') - 1406 m
- Folkvanger Valley (S77° 35.771' , E160° 58.442') – 1486m
- Knobhead (S77° 55.618' , E161° 33.735') – 1472m
- New Mountain (S77° 52.186' , E161° 13.556') – 1306m
- Rotunda (S78° 01.696' , E161° 36.181') - 1987m

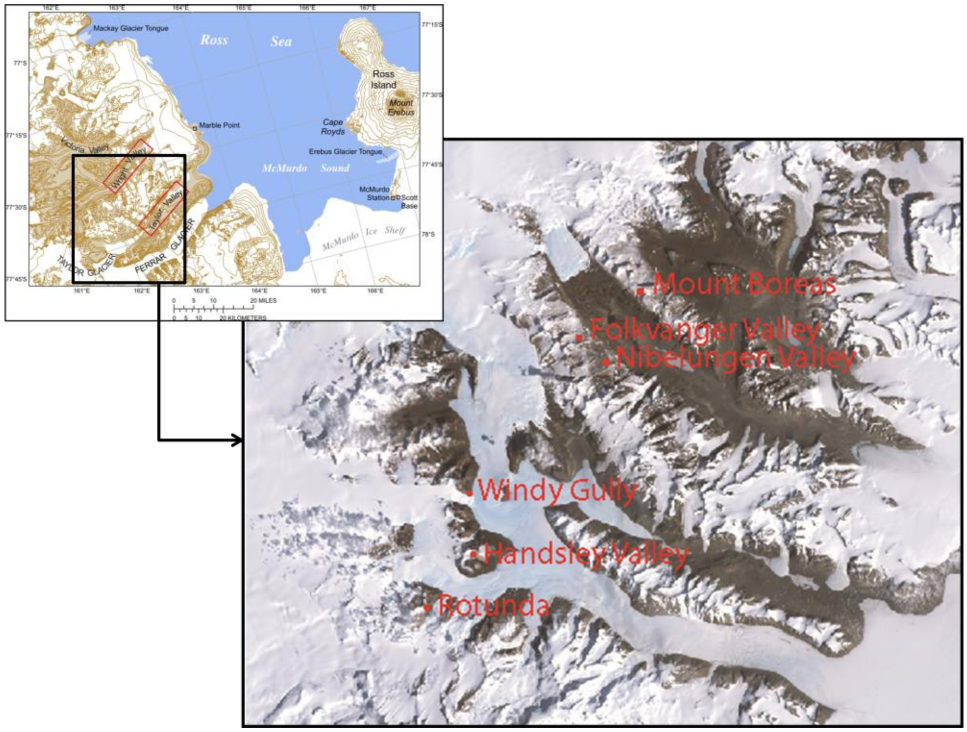

Figure 1.1 location map of field area sites in the Wright Valley, Taylor Valley and sites further south in Southern Victoria Land

1.1.1 Mount Boreas (08-11 Jan 2008)

The first field stop, Mt Boreas, was more an extra site visit for MSc student Greer Gilmer. The site, for the author, was as an introduction and familiarization to the units to be studied in the field. A single stratigraphic section was measured here and a clast count was executed on the HES for later QFL analysis for Greer Gilmer's thesis. The base camp and travelled routes can be seen in Figure 1.2. The characteristics of the Heimdall Erosion Surface at this location will be included in later chapters.

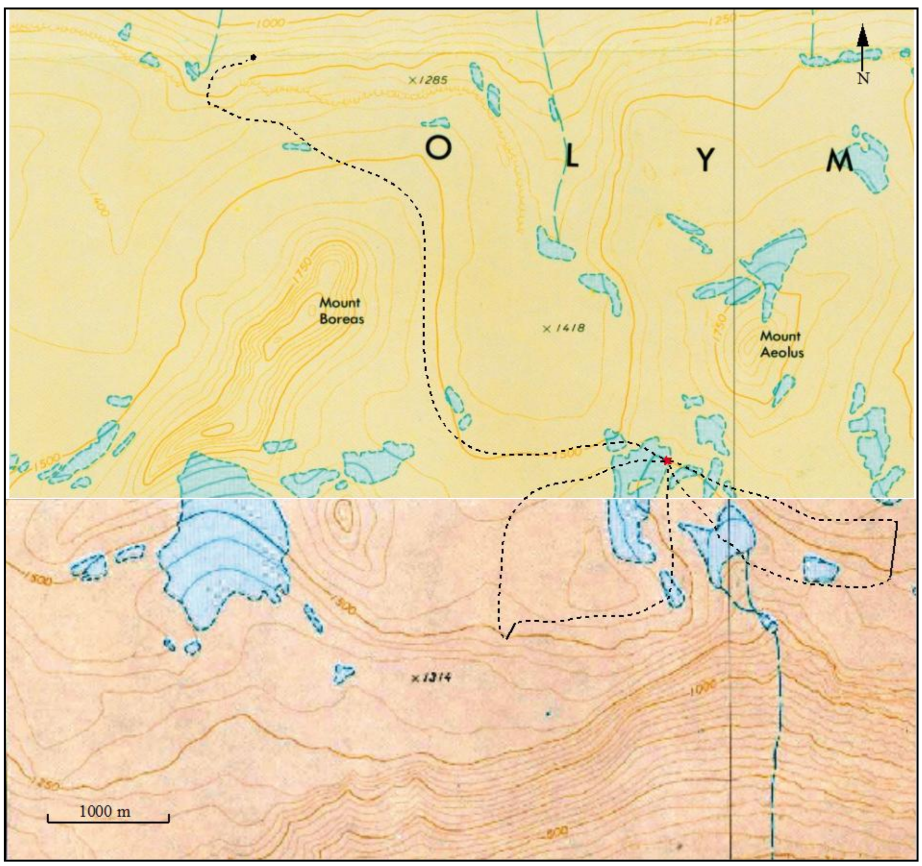

Figure 1.2 Location and route map for Mt Boreas and Mt Aeolus (08-11 Jan 2008) (USGS, 1977 & 1977c, Gilmer, 2008)

1.1.2 Nibelungen Valley (12-17 Jan 2008)

The Nibelungen Valley was one of the longest spent field areas in the season but also proved very difficult in terms of accessibility and continuous exposure. Areas of interest, such as the Kukri Erosion Surface, had their best exposure in inaccessible areas. The exposures had to be observed from a distance resulting in estimations in terms of thickness for key basal units such as the Windy Gully Sandstone Formation. Although observed from a distance, this outcrop proved important for comparison of Kukri exposures further south.

In addition the New Mountain Sandstone Formation was often difficult to get full stratagraphic successions so partial sections were recorded and give a minimum thickness. East of the campsite was the area known as Plane Table, where the Plane Table Member of the lower New Mountain Sandstone Formation exists. This greener tinged Quartz sandstone was only observed in this site and is believed to have a relationship with the below Terra Cotta Siltstone Formation.

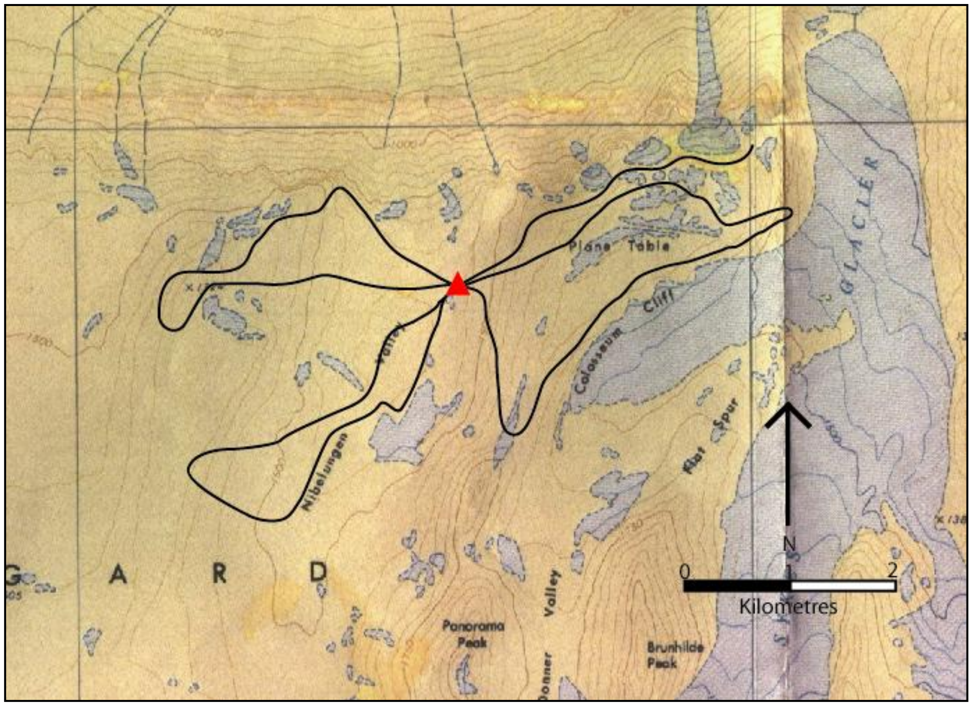

Figure 1.3 Location and route map for Nibelungen Valley (12-17 Jan 2008) (USGS, 1977)

1.1.3 Folkvanger Valley (18-21 Jan 2008)

Only a short time was spent at this field site as the exposure was relatively poor. Sites further east of camp in the Folkvanger Valley provided continuous exposure of the HES. In this case the HES formed a terrace where the field group could follow the HES laterally over 1km. This allowed good exposure of the Heimdall Erosion Surface and the associated basal conglomerate directly above.

1.1.4 Knobhead (Handsley Valley) (22-28 Jan 2008)

Fieldwork at Knobhead consisted of long sections covering a majority of the Windy gully and New Mountain Sandstone Formations. A majority of the sections were measured along the exposed ridge west of camp (see figure 1.5

A&B) but observations of the lower basal units and Altar Mountain Formations were made through the teams movements (see figure 1.5). The stratagraphic sections were broken up due to the changes in accessibility. Measuring of the sections were therefore restarted laterally along the face where access was better. The Knobhead field site was also where the Heimdall was first seen as a conformable succession rather than a truncation in the earlier sites

Figure 1.5 A&B Exposed ridge of lower Taylor sediments from side view, A, and head on view B

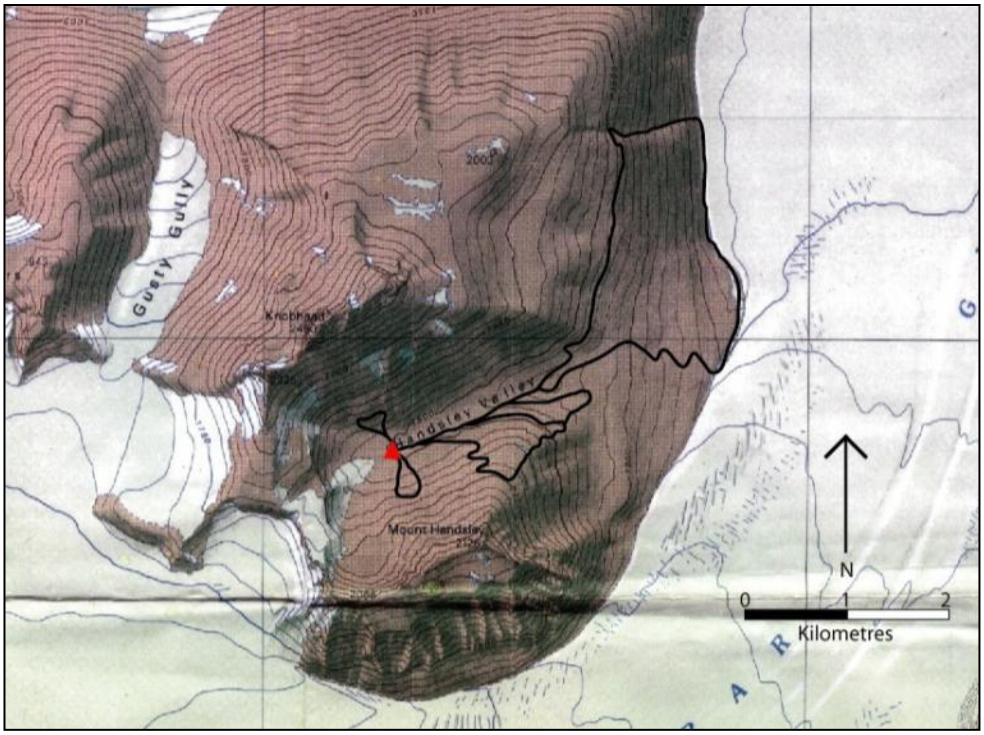

Figure 1.6 The Knobhead field area and paths taken throughout the time spent.

1.1.5 New Mountain (Windy Gully) (29-31 Jan 2008)

The New Mountain field site proved valuable for the investigation and interpretation of the Kukri Erosion Surface (KES). Here the relief of the KES was sufficient to vary the full thickness of the Windy Gully Sandstone Formation (WGSst) and therefore showed a variation of interaction and changes in environmental conditions throughout the cross bedded sandstones. The gradational contact between the WGSst and the Terra Cotta Siltstone Formation was also seen before an extensive dolerite sill separated the sediments. The New Mountain Sandstone Formation was seen above the sill and measured by handheld GPS due to time constraints and the notable consistency of the sedimentary structures. Two main paths were taken to observe the relevant sedimentology as it was separated due to a large dolerite sill (see figure 1.7)

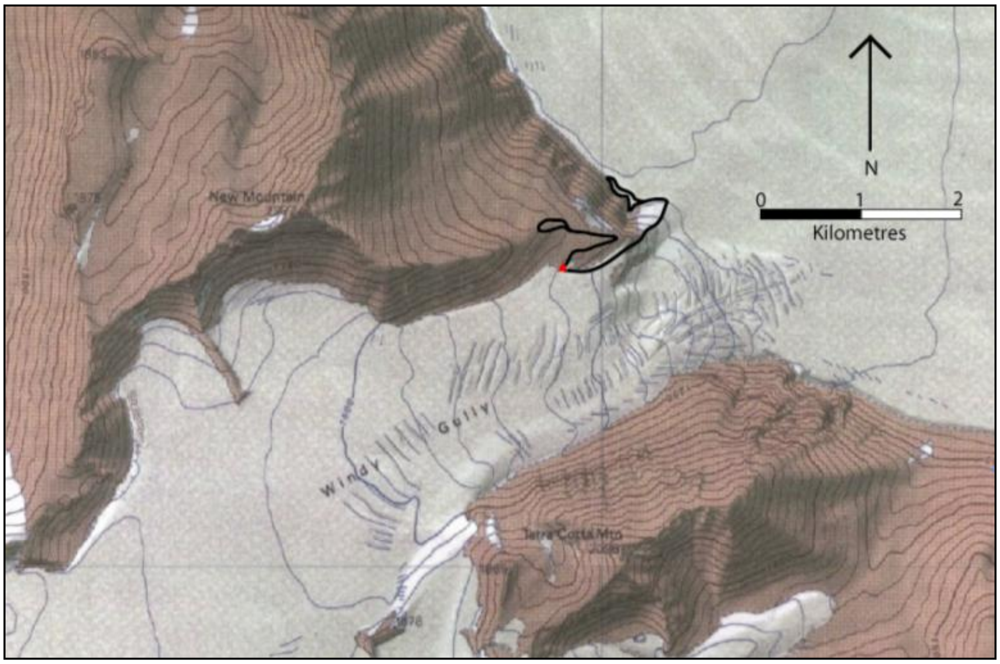

Figure 1.7 paths taken above and below the extensive dolerite sill that separates the sediments, New Mountain

1.1.6 Rotunda (01-04 Feb 2008)

The rotunda field site concentrated on the location of the HES horizon and sediments above and below. Only a short time was spent at this site so therefore only the New Mountain Sandstone and Altar Mountain Formations were measured at this location. This location was at the southern most point of the field area. The area consisted of snow covered low angle slopes making exposure inconsistent (see figure 1.8)

Figure 1.8 View of the outcrops looking north from the camp site, Rotunda

1.2 Methodology

The majority of sites were chosen before the field season from literature review and map. Observations were made at each site as to identify key stratigraphic locations, such as the Heimdall Erosion Surface (HES), and then appropriate sites were chosen to measure sections for stratigraphic columns.

Representative rock samples were gathered throughout the sections whilst beds and structures were measured wherever applicable or possible, including paleocurrent/cross-bed directions and clast counts. Later thin section analysis, zircon preparation and analysis of field data was carried out at University of Canterbury (UC) whilst specific zircon mounting and dating was undertaken at Australian National University (ANU), Canberra in collaboration with Dr Mike Palin from the Geological Department, University of Otago.

The 2008 field party included Dr Margaret Bradshaw, Dr John Bradshaw and MSc student Greer Gilmer.

1.2.1 Stratigraphic Columns

Stratigraphic sections were measured throughout the field area where exposure was continuous, and preferably where the HES was present as this was the primary focus of the research. This horizon proved important both for stratigraphic perspective and to observe the characteristic change as we moved laterally from site to site. The sections were measured by means of a ruler or tape measure and rounded to the nearest 10cm; beds <10cm were grouped together. If the section had poor exposure, by rubble, scree or snow, we would move laterally along an identifiable horizon and continue. The Kukri Erosion

Surface (KES) was incorporated in some cases but, as the thickness between the erosion surfaces was significant, it was rare to get the two in a single continuous section.

The purpose for the stratigraphic columns is to allow a clear representation of field description to interpret the depositional setting. These columns preferably include the members either side of the HES, the New Mountain Sandstone and Odin Arkose members, and in most cases the lower units, the Windy Gully Sandstone and Terra Cotta Siltstone Formation. The stratigraphic columns are also simplified and incorporated into fence diagrams to show lateral variations and such aspects as unit thickness and lateral change of specific horizons (i.e. the HES) either by lithological or depositional change.

The stratigraphic columns were constructed at University of Canterbury (UC) using Adobe Illustrator (9.0.1).

1.2.2 Paleocurrent Direction

Cross beds, ripple cross-laminations and trough channel axis were measured throughout the stratigraphic sections for information on changing paleocurrent directions. Cross bed foresets were the most common structures measured and a majority of the main bed structures were either flat lying or very shallow in dip therefore the foreset dips seldom needed any correction for post depositional tilting. Paleocurrent measurements were confined to the Windy Gully Sandstone, the New Mountain Sandstone and the Odin Arkose Member due to their cross bedded and rippled nature. The measurements were taken by a standard Brunton geologic compass and their position recorded by hand-held Garmin GPS.

Measurements were later corrected by approximately 21° for the Antarctic magnetic variation, obtained from www.ngdc.noaa.gov/seg/geomag/redirect.shtml, and constructed into a series of rose diagrams to show any change of flow direction throughout the units and different sites. The rose diagrams were constructed by means of a database Grapher 7.

1.2.3 Thin Sections and Point Counts

Hand specimens were taken throughout the stratigraphic sections at semi-regular intervals as to get representative samples to both examine any changes both as hand specimen and later as thin section. Samples were also taken where exotics were observed, such as rip-up clasts deposited on erosion surfaces. Pebble counts were also taken in the field for a rough estimation of to compare with thin section count data.

The thin sections were cut later at University of Canterbury both for description of representative samples and point count data and then for feldspar identification. The chosen sections were mounted on glass slides using epoxy resin and ground to 0.03mm thick. The slides chosen to be stained for type of feldspar were left slightly thicker as the etching process can affect thinner slides adversely. The staining process included the use of Hydrofluoric acid (HF) vapor to etch the slide sample. This was followed by two different stains for the particular feldspars; sodium cobalti nitrate for alkali feldspar (stains yellow) and rodizonic acid for plagioclase feldspar (stains orange/red). These techniques are outlined in Practical Sedimentology (Lewis, 1984).

The point counting of the stained slides was executed on a Prior Swift James automated point counter and recorded on Excel spreadsheets (Appendix

B1). The data from the point counts were used to produce QFL diagrams to identify the nature of source and aid other provenance interpretation techniques, such as detrital zircon U-Pb dating.

1.2.4 LA-ICP-MS (Zircons)

Heavy minerals (HMs) such as Zircons are relatively rare in the samples collected but provide valuable provenance information, not the age of deposition of the sediment but the age of crystallization of the parent rock and therefore show any change in source of such a parent rock through the stratigraphic record.

Four samples were chosen from representative stratigraphic levels. The samples were taken from the bottom of the New Mountain Sandstone Member, above and below the HES and towards the top of the Odin Arkose Member. These samples were crushed and ground down to a consistent powder no finer than approximately 60μm and no coarser than approximately 125μm. The zircons were then separated using Lithium Heteropolytunstates (LST) heavy liquid with a density of 2.85$\pm$0.02g/ml through a separation funnel. The separated HM's were caught in paper filters and washed thoroughly in distilled water before individually picking zircons under binocular microscope. Although not all of the samples produced the preferable 120grains for a 100 spot count for LA-ICP-MS laser ablation, the samples were reasonably consistent.

The zircon samples were then mounted in epoxy resin and polished to expose the grains. They were then dated using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) at ANU, Canberra.

1.2.5 Cathodoluminescence (SEM-CL)

The SEM-CL was used to support the LA-ICP-MS analysis for the zircon provenance. The cathodolumescence shows the zoning in the mineral, its physical condition, and whether the zircon rim or core had been sampled. The samples were gold and carbon coated using the Emitech K550x for 20mA at 1.2kV, providing a 50 Å coating. A Leica S440 SEM with a Gatan Oxford miniCL attached was used to analyze the samples.

1.3 Thesis Structure

The overall introduction to the thesis, description of field areas visited and the methodology are described in this chapter (Chapter 1). Chapter 2 describes the geological background and different conflicting interpretations of the formations studied in the area. This includes the Basement rocks in the area and the intrusive bodies.

Chapters 3 to 9 describe and discuss the geological units throughout the field in stratagraphic order. Emphasis is taken on how the stratigraphic units change laterally from site to site. The author suggests likely paleoenvironmental interpretations with the combination of sedimentary structures, trace fossils and paleocurrent measurements. The formations are divided into lithofacies as to separate environmental conditions and develop a systematic progression of the sediments' depositional proxies.

Chapter 10 studies and concludes the lower Beacon rocks' provenance through a range of techniques including LA-ICP-MS U-Pb zircon dating and SEM-CL of the New Mountain Sandstone and Altar Mountain Formations.

Chapter 11 combines sequence stratigraphy to show sedimentary progression with relative sea level changes and associated erosion surfaces. This interpretation results in an environmental interpretation and conclusions of the lower Beacon sediments from the basal Kukri Erosion Surface to the Altar Mountain Formation.

2. Chapter 2- Geological Background

2.1 Introduction

This Chapter outlines previous research on the members of the lower Beacon Supergroup, in particular the environmental interpretations of such members (see figure 2.1). Argument over the interpretation of depositional settings of formations within the Beacon Supergroup is based on evidence and interpretation of features such as sedimentary structures, facies relationships and trace fossils. The focus of this research is the interpretation of the Heimdall Erosion Surface but this incorporates units above and below for such interpretation.

In Southern Victoria Land (SVL) the quartzose sedimentary successions of the Beacon Super Group are underlain by plutonic and metasedimentary basement of the Koettilitz Group and Granite Harbour Intrusives and intruded by the Ferrar Dolerite. Previous studies in the area span back as far as Scott's 1901 expedition (Ferrar, 1907) followed by further mapping in 1910 by Debenham (1921) as part of the Terra Nova expedition. The area was not visited again until the International Geophysical Year (IPY) in 1957-58 when major work was done in the Dry Valleys by researchers from Victoria University (McKelvey and Webb, 1959, 1962; Webb and McKelvey, 1959; Allen and Gibson, 1962; Webb, 1963 More later refs)

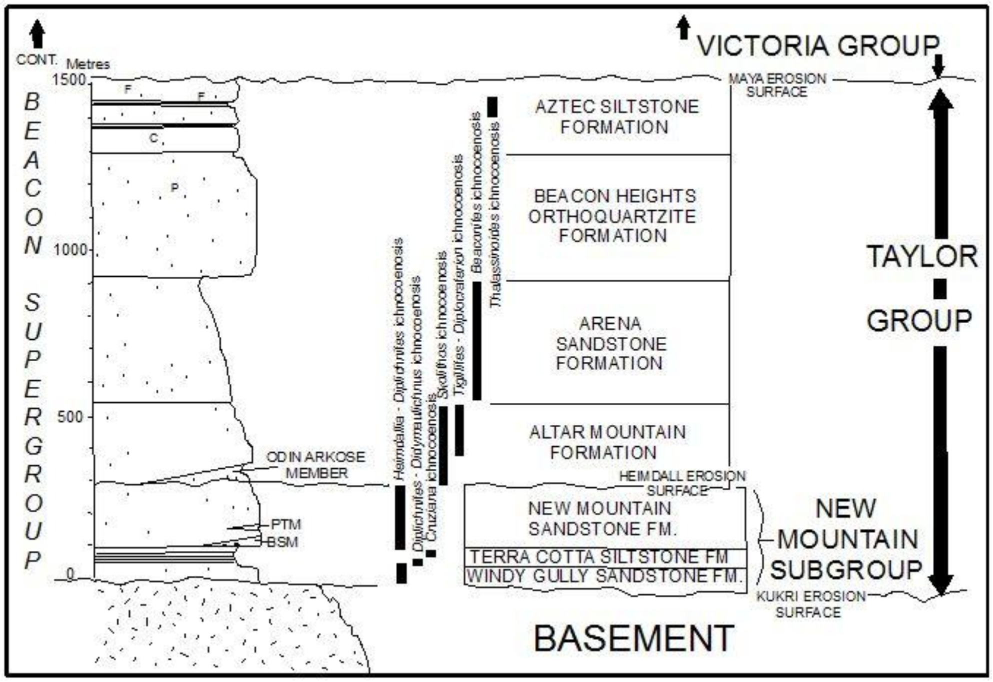

Figure 2.1 Stratigraphy of the Taylor Group (lower Beacon Supergroup) in southern Victoria Land (Bradshaw 1981)

2.2 Basement

Basement in Southern Victoria Land consists of plutonic and metasedimentary rocks of the Koettilitz Group, the Skelton Group and Granite Harbour Intrusives which have been later intruded by Ferrar Dolerite (Allibone et al., 1991; Isaac et al, 1995 and references therein).

2.2.1 Koettilitz Group

Grindly and Warren (1964) introduced the Proterozoic Koettilitz Group and initially described them as metasedimentary rocks present in the Koettilitz Glacier, Ferrar Glacier, in the Dry Valleys area. This also included the Asgard Formation of McKelvey & Webb (1962). The Koettilitz Group was later subdivided into the Marshall, Salmon Marble and Hobbs formations (Allibone et al., 1991). The Koettilitz Group metasediments are mapped in a 1-4km wide belt that extends across the southern side of the Kukri Hills to the northern face of the Asgard Range, east of the Nibelungen Valley; granitoid intrusions may disrupt the continuity of the belt (Allibone et al., 1991).

The Koettilitz Group is comprised of interlayered sequences of marble and psammitic schist, with significant amphibolitic schist and feldspathic gneiss. Koettilitz Group rocks in some areas, such as the Thundergut, have also undergone upper amphibolite facies metamorphism (Allibone et al., 1991). In addition, the quartzofeldspathic gneiss and schist with accessory biotite and amphibole occur along the eastern side of the Koettilitz belt on both sides of the Taylor Glacier. These rocks are interpreted as meta-arkose on the basis of their felsic composition (Allibone et al., 1991; Isaac et al, 1995 and references therein).

The structure of the Koettilitz Group can be linked to two periods of deformation (Allibone et al., 1993 & 1993a). This is associated with S-surfaces, fold axis and lineation, termed D1 and D2. Rootless, mesoscopic isoclinal folds are the earliest structures recognized but are altered in places due to subsequent refolding and flattening from the second phase of deformation.

Radiometric of D2 dating by Rb-Sr determinations in the Wright and Victoria valleys have given a metamorphism age of 670Ma (Late Precambrian) (Adams & Whitla, 1987).

2.2.3 Granite Harbour Intrusives

The Granite Harbour Intrusives name is used for all Paleozoic and older granitoid rocks in Southern Victoria Land and is divided into three petrogenetically distinct suites (DV1a, DV1b & DV2) depending on composition and date of emplacement (Allibone & Cox, 1993). These range from highly deformed orthogneiss through to undeformed relatively high level plutons (Allibone et al., 1991). The older Dry Valleys1a (DV1a) suite is comprised of the Bonney, Catspaw, Denton, Cavendish and Wheeler Plutons. The Dry Valleys 1b (DV1b) suite is comprised of the Hedley, Valhalla, St Johns, Dun, Calkin and Seuss Plutons. These were emplaced prior to swarms of Vanda mafic and felsic dikes and consist of monzodiorite to granodiorite and hornblende orthogneisses (Allibone et al., 1993 & 1993a). Both the DV1a and DV1b suites are time transgressive and date between 589 and 490Ma with early intrusions being emplaced during latter stages of deformation in the Koettilitz Group.

The Dry Valleys 2 (DV2) suite, consisting of the Pearse and Nibelungen Plutons (plus several smaller unnamed plugs) was emplaced between 480 and 455Ma. These are younger granitoids that postdate the majority of the Vanda dikes (Allibone et al. 1993 & 1993a). For locations of local plutons see Figure 2.2.

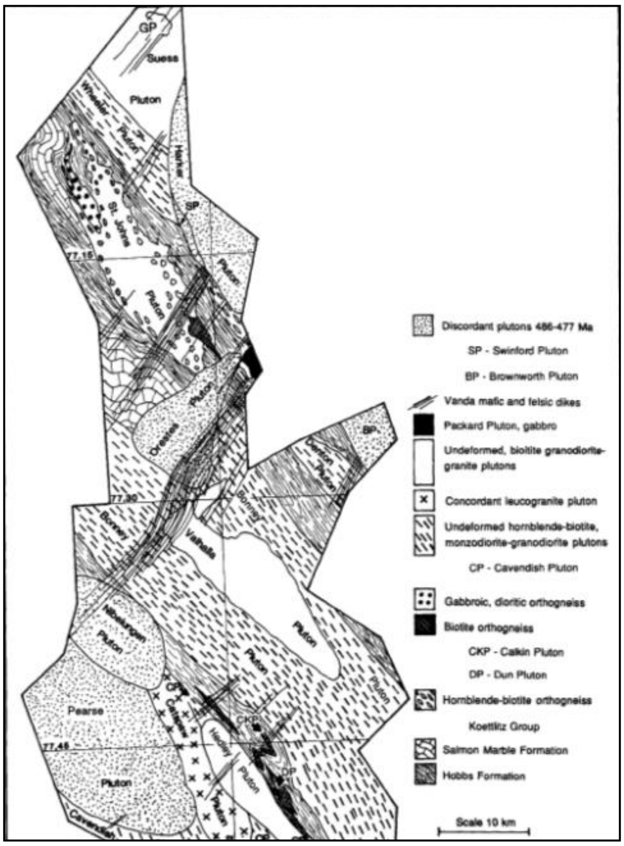

Figure 2.2 Inferred basement geology of the Dry Valleys showing pluton orientation and placement (Allibone *et al*, 1993a)

2.2.4 Skelton Group

The Skelton Group forms one of several Proterozoic-Cambrian metasedimentary units that form basement of the Ross Origin in East Antarctica. It was deposited in one or more phases of rifting that accompanied breakup of the Precambrian supercontinent Rodinia. Detrital zircon ages of the Neoproterozoic Skelton Group is dominated by a ca. 1300-950Ma age range similar to those of the Beardmore Group East Antarctica and Adelaidean succession of South Australia (Wysoczanski & Allibone, 2004).

2.2.5 Ferrar Dolerite

The Ferrar Dolerite is the most widespread of the Ferrar Supergroup and forms post-depositional sills and dikes throughout the Transantarctic Mountains and is at its best exposure in Southern Victoria Land. The sills commonly intrude the beacon sediments with a range from 100-300m and on occasion exceed 1000m (Kyle *et al.,* 1980). The sills predominantly affect the

Beacon sediments above the Kukri Erosion Surface but do not intrude lithologies below thus postdating the KES (McKelvey *et al.*, 1977). The sills commonly occur above the KES but not below, in basement, thus preserving thin packages of Beacon sediments. The age of the Ferrar Supergroup is best constrained by U-Pb dating at 179+/-7 Ma (Kyle *et al.*, 1980). In many cases in this study it has been difficult to determine the true thickness of the Beacon units due to the intrusion of the dolerite sills and the separation into isolated strata as a result.

2.4 The Beacon Supergroup

The Beacon Super Group (Devonian to Triassic) is comprised of an approximately 2.5-3km thick sequence of almost horizontal, unfolded, quartzose, cratonic sandstones with finer horizons that rest unconformably on basement rocks (Ordovician and older) of the East Antarctic Craton and older throughout the Transantarctic Mountains (Bradshaw, 1981; Barrett, 1981; McKelvey *et al*, 1977; Isbell, 2004). The sequence is subdivided in South Victoria Land into a younger Victoria Group (Permo-Triassic) and an older Taylor Group (Devonian).

A majority of the Taylor Group in southern Victoria Land is highly quartzose in composition, indicating prolonged chemical weathering and recycling of sediments in a long lasting, relatively quiescent tectonic setting (Dickenson, 1985; Chandler, 1988). Deposition occurred within a transantarctic basin believed to have extended along the edge of the East Antarctic Cration in early Beacon time, either as a marginal, passive margin or cratonic basin (Isbell, 2004).

The sedimentary components of interest in the Taylor Group (Lower Beacon Supergroup) in Southern Victoria Land for this thesis include the New Mountain Subgroup (Windy Gully Sandstone , Terra Cotta Siltstone and New Mountain Sandstone Formation). The New Mountain Subgroup is bound at its base by the Kukri Erosion Surface (KES) and at the top by the Heimdall

Erosion Surface. Above the HES is the Altar Mountain Formation, in particular the Odin Arkose Member of particular interest for this thesis.

2.4.1 Kukri Erosion Surface (KES)

The basal unconformity between the Beacon Supergroup and basement rocks is known as the Kukri Erosion surface (KES) or, in some instances, the Kukri Peneplain (Grindley, 1963; Skinner, 1965; McKelvey *et al.* 1977; Plume, 1978; Anderson, 1979; McElroy & Rose, 1987; Barrett, 1991; Isbell, 2004). It is referred to as a nonconformity to angular unconformity that extends throughout much of the Transantarctic Mountains (Isbell, 2004).

The KES is considered to be planar with a relief of only a few tens of meters (Grindley, 1963; McElroy & Rose, 1987; Barrett, 1991), however, Skinner (1965), Anderson (1979), Bradshaw (1981) and Isaac *et al.* (1996) described high relief (up to hundreds of meters) in the Olympus Range, between Nimrod and Byrd glaciers and in southern Victoria Land. At one particular location Anderson (1979) described 700m of offset cutting the Shackleton limestone with paleokarst topography just south of Byrd Glacier. Significant local relief occurs on the KES in Southern Victoria Land (Bradshaw, 1981; Isaac *et al.*, 1996).

Contacts on the KES differ due to the relief and basement topography, in particular the highs, and can be inferred in certain situations. These include 1) where sediments onlap onto basement, 2) where the younger Heimdall Erosion Surface has removed the KES or 3) the lower formations of the Beacon Supergroup are missing (McKelvey *et al.* 1977; Isaac *et al.* 1996).

The basement rocks are also intruded by large diabase sills hundreds of meters thick (DV2). Variable depth in weathering in the basement rock is reported (McKelvey & Webb, 1959). Isbell (2004) suggests the presence of deeply weathered basement rocks is due to an extended period of non-erosion and/or non-deposition event before Taylor Group sedimentation.

2.4.2 Windy Gully Sandstone Formation (WGSst)

The name of this particular formation is derived from Windy Gully, a small ice-filled valley that cuts through the Quartermain Range between New Mountain and Terra Cotta Mountain. The Windy Gully Sandstone is a predominantly cream to pale brown, planar and cross-bedded, indurated but not cemented, well sorted medium sandstone with rounded quartz grains, characterized by meter thick intervals of completely burrowed *Heimdallia chatwini*. Other trace fossils are present within the formation, such as *Diplichnites goudi* (a parallel type track way) that are common on foresets of the cross-beds, and *Didymaulichnus nankervisi* on the bottom of bioturbated beds (Plume, 1978; Bradshaw, 1981).

Granule to pebble conglomeratic sequences make up the basal meters (up to 3m) which contains clasts of vein quartz, schist and granite ranging from granule to boulder (<2m in diameter) in size (McKelvey *et al.*, 1977; Plume, 1978). The upper sequence consists both of massive and meter thick beds of planar-bedded and trough or tabular cross-stratified medium sandstone with flaggy partings. Rare mudstone layers are present in the basal few meters and usually contain desiccation cracks (cracks formed by the drying thus shrinkage in finer sediments). Paleocurrent measurements of cross-bedding within the Windy Gully Sandstone, south of the Asgard Range, indicate paleoflows toward the West, although ripple crest and current parting lineation measurements are more diverse (Plume, 1978).

With a maximum thickness measured at 120 meters (east of the Borns Glacier), the Windy Gully Sandstone occurs extensively throughout the Asgard Range and as remnants on the Kukri and Friis Hills and southwest of the Rhone Glacier. In the Asgard Range it is particularly well exposed in the Fenrir, Tiw, Odin and Nebilungen Valleys and rests unconformably on the Kukri Erosion Surface (Plume, 1978).

Bradshaw (1981) suggests a tidally active marine depositional environment, predominantly in active channels and on the surrounding tidally emergent bioturbated sand flats whereas Plume (1982) suggests large braided fluvial streams and interacting aeolian sand dunes.

2.4.3 Terra Cotta Siltstone Formation (TCzst)

Named after a small peak on the eastern side of Windy Gully (Terra Cotta Mountain), the Terra Cotta Siltstone Formation consists predominantly of maroon, purple, green and grey siltstone, shale and mudstone. Subordinate cream sediments also alternate in cyclic sequences (McKelvey *et al.* 1977; Plume, 1978). Thickness of this formation ranges from its thickest (82m) at Mt Kempe in the Royal Society Range to its thinnest (8m) on Mt Jason in the Olympus Range (Plume, 1978; Bradshaw, 1981)

The lower contact of the Terra Cotta Siltstone Formation is gradational with the underlying Windy Gully Sandstone Formation whereas the upper contact with the New Mountain Sandstone Formation is very sharp (Plume, 1978). Such a sharp contact has created some debate in the past noted as “A decided break in sedimentation” by Zeller *et al.* (1961).

A range of sedimentary features are seen within the Terra Cotta Siltstone Formation. These include; straight crested, symmetrical ripples, mud cracks, feeding burrows and tracks, mudstone clast conglomerates, loading features, carbonate concretions and poorly developed vein networks (Plume, 1978). Plume (1982) supports a lacustrine paleoenvironment with ^{13}C values from carbonate concretions, siltstone lithofacies and the lack of body fossils and the sedimentary structures alone indicate a shallow water environment.

Bradshaw (1981), however, supports a marine environment due to the presence of trace fossils *Cruziana* and *Rusophycus* (oblique scratch marks that can be closely related to forms attributed to trilobites). She suggested that the Terra Cotta Siltstone Formation was deposited in a coastal lagoon cut off by a barrier beach. Other trace fossils including *Diplicnities* and *Didymaulichus* suggest arthropod movement through channels linked to the lagoon from the sea. Observed mud cracks within the formation indicate extreme low tides or abrupt change in salinity, related to a dynamic interaction with the sea (Bradshaw, 1981).

2.4.4 Windy Gully Erosion Surface (Terra Cotta Siltstone Erosional Contact)

The Windy Gully Erosion Surface is represented by the very sharp, and in places erosional, contact between the Terra Cotta Siltstone and New Mountain Sandstone Formation. It was first suggested by Hamilton & Hayes (1965) stating that the contact was a probable major disconformity. The Windy Gully Erosion Surface was later examined in the Beacon Heights area and at Mt Heimdall by McKelvey *et al.* (1972) and was referred to as "not regionally important" (Plume, 1978). In the field, the Windy Gully Erosion Surface was identified by the presence of Terra Cotta rip-up clasts in the Basal Conglomerate Lithofacies of the above New Mountain Sandstone Formation.

2.4.5 New Mountain Sandstone Formation (NMSst)

The New Mountain Sandstone Formation is a light tan or buff, medium to coarse-grained quartzose sandstone that lays both conformably and unconformably on the Terra Cotta Siltstone Formation. Interbedded siltstone lithologies are found both at the top and base of the formation. Sedimentary features throughout the formation include distinctive large scale cross-bedding, desiccation cracks ripple assemblages and abundant trace fossil fauna (both horizontal and vertical) (Plume, 1978).

Towards the south, the New Mountain Sandstone has an abrupt contact with the Terra Cotta Siltstone Formation. Directly above the basal contact the sedimentary structures change laterally from small scale cross bedding (0.5-1.1m sets), as at Table Mountain, or thick plane laminated interval, as at New Mountain (Bradshaw, 1981; Plume 1982). However, towards the north the Boreas Subgreywacke Member appears at the base of the formation and is coarsest at Mt Boreas, where it directly overlies basement (Bradshaw, 1981).

The New Mountain Sandstone Formation consists predominantly of cross-bedded, medium to coarse-grained, quartzose sandstone (0.5-2m thick sets) alternating with highly bioturbated, near horizontal sandstones, very similar to the Windy Gully Sandstone (Bradshaw, 1981). The upper part of the formation contains locally constrained, very large cross-beds (2-8m thick) that often oppose direction of the lower medium scale cross-beds (Plume, 1982).

The sandstone is thickest (295m) at Miller Glacier (McKelvey *et al.* 1977) and is found as far north as Mt Leland and as far south as Rotunda (Plume, 1978; Isaac *et al.* 1995). The New Mountain Sandstone Formation thins towards the north and west. Furthermore, towards the top of the formation in the south, the New Mountain Sandstone contains *Scolithos* ichnocoenosis ranging in thickness (17-28m) (Barrett & Webb, 1973; Bradshaw, 1981). Bradshaw (1981) suggests that the appearance of this ichnocoenosis reflects a marked change in environment before the cessation of the New Mountain Formation deposition.

Bradshaw (1981) suggests a similar environment as the Windy Gully Sandstone Formation with tidally effected sand flats laced with channels and differing paleocurrent directions at the base of the formation, identified by Plume (1982), may reflect tidal or wave action on the hypothesized barrier beach flanking the “Terra Cotta lagoon”. Plume (1982) suggests an aeolian dune setting and a non marine environment similar to the deposits of the Brahmaputra River, India due to 180° opposing paleocurrent directions, scour and fill channels and thin siltstone beds. However, Bradshaw (1981), notes rare *Heimdallia* and *Diplichnites* within the large cross-bed sets and suggests and subaqueous origin more probable.

Wizevich (1997) interprets a fluvial and aeolian depositional setting in the Table Mountain area due to the presence of ‘super sized cross beds, and ‘pin stripe appearance’. However, Barrett and Kohn (1975) point to paleocurrent directions predominantly flowing westward and suggest a shallow marine environment with the migration of sand waves producing large scale cross beds. Barrett and Kohn (1975) suggest a cessation of deposition as a result of uplift in the north and resulted in erosion and the appearance of the HES.

2.4.5aBoreas Subgreywacke Member

Located on the northwest flank of Mt Boreas, Olympus Range, the Boreas Subgreywake Member consists of extremely hard black-green beds of breccia, conglomerate, sandstone and argillite at the base of the New Mountain Sandstone where it lies directly on basement (Plume, 1978; Bradshaw, 1981). The maximum thickness of the member is approximately 16-17m thick and consists of alternating beds of argillite and extremely poorly sorted coarse sandstone and conglomerate beds less than 50cm in thickness. Granite clasts, quartz and feldspar grains are as large as 3cm in diameter and elongation of the grains show some imbrication. Angularity of the clasts indicates deposition close to source and the weathering of the clasts is suggested to be physical rather than chemical (Plume, 1982). At Plane Table the unit is comprised of fining upward cycles from reddish-brown, coarse grained sandstone to well sorted, massive, white sandstone (Plume, 1978). Although the unit is very different at the two locations, the more quartzose New Mountain Sandstone overlies both deposits thus placing them in the same stratigraphic position; however the lateral extent of the member is questionable due to the lack of exposure and clear definition (Plume, 1982).

Interpretation of the Boreas Subgreywake Member varies from a granitic source debris flow (Bradshaw, 1981) or an alluvial fan (Plume, 1982).

2.4.5bPlane Table Member

The Plane Table Member occurs towards the base of the New Mountain Sandstone and is located on the east face of Plane Table in the Asgard Range (Plume, 1978). It is only 5-9m thick and has an approximate lateral extent of 1km. This dark purple and dark olive-green member is comparable to the Terra Cotta Siltstone Formation and is interpreted as a lacustrine deposit (Plume, 1982).

2.4.6 Heimdall Erosion Surface (HES)

The Heimdall Erosion Surface (HES) is a disconformity/paraconformity that separates the quartzose New Mountain Sandstone Formation from the overlying quartzo-feldspathic to arkosic Altar Mountain Formation. The HES is confined to southern Victoria Land and changes laterally from a sharp contact in the north to a conformable contact in the south (McKelvey *et al.* 1970, 1977). In the north the HES truncates the New Mountain Sandstone Formation from the above Odin Arkose Member. In some instances the HES interacts with basement plutons thus leaving no evidence of the lower Taylor Group sections whatsoever (McKelvey *et al.* 1977). This indicates a basal high, for example, at Balham Valley (Bradshaw 1981). Furthermore, the HES converges with the basal Kukri Erosion Surface (KES) in the Wheeler and Balham Valleys, and at Packhard Glacier in Southern Victoria Land (McKelvey *et al.* 1977). Moving south, the HES becomes more conformable where continuous sedimentation occurs between the New Mountain Sandstone Formation and the Altar Mountain Formation, identified as a influx of feldspar into the quartzose sandstones (McKelvey *et al.* 1977, Plume, 1978)

2.4.7 Altar Mountain Formation

Named after Altar Mountain in the Quartermain Range, the basal beds consist of the Odin Arkose Member, an arkosic to slightly feldspathic, cross-bedded, coarse quartz sandstone or pebble-granule conglomerate (McElroy, 1969). The remainder of the Altar Mountain consists of frequently interbedded quartzose sandstones and subordinate maroon and green siltstones and mudstones. Furthermore, a cyclic relationship between the lithologies is often apparent with cycles having erosive basal contacts and basal conglomerates composed of rip up clasts and quartz granules and pebbles (McElroy, 1969; Isaac *et al.* 1995). The sandstones often contain ferruginous concretions, speckles and pyrite cubes and sedimentary structures include trough and planar cross-beds, ripples, mud cracks, millimeter scale laminations and structures common to dewatering (McKelvey *et al.* 1977; Isaac *et al.* 1995).

The Altar Mountain Formation has a maximum thickness (235m) at West Beacon and is found from Mt Seuss, in the north, to Rotunda (55m), in the south (McKelvey *et al.* 1977; Bradshaw, 1981). This formation represents the lowest part of the Victoria Group and overlies the New Mountain Formation. However, it is also laid directly onto basement in the north (Barrett & Kohn, 1975; Savage, 2005)

Measurements from cross-beds within the Altar Mountain Formation indicate a northwest trend in flow and trace fossils include *Tigillites-Diplocraterion*, *Scolithos* and *Beaconites antarcticus* (Barrett & Webb, 1973; Barrett & Kohn, 1975; Bradshaw, 1981; Isaac *et al.* 1995).

Paleoenvironmental interpretations include Barrett & Kohn (1975), suggesting the Altar Mountain Formation was deposited in a coastal-marine environment (due to the presence of siltstone and mud cracks), and Bradshaw (1981) suggesting a maximum marine transgression forming a shallow marine setting (due to trace fossil assemblages).

2.4.7a Odin Arkose Member

The Odin Arkose forms the basal member of the Altar Mountain Formation. It is a coarse, feldspathic sandstone, has a maximum thickness at Rotunda (55m) is difficult to determine due to the gradational contact (10-60m) to the above Arena Sandstone (Barrett and Webb, 1973; McKelvey *et al.* 1977; Bradshaw, 1981). It consists of a basal conglomerate which contains rounded to well rounded quartz pebbles and other lithologies. The basal conglomerate is overlain by trough and planar cross-bedded arkosic medium sandstone with *Skolithos* trace fossils and current flow trending from west to southwest (Barrett and Webb, 1973; Barrett and Kohn, 1975; McKelvey *et al.*, 1977; Bradshaw, 1981; Isaac *et al.*, 1995)

The Odin Arkose Member overlies the HES and buries the Balham Valley basement high in the north. The Odin Arkose is found as far north as Mt Seuss where it is known as the Sperm Bluff Formation (Savage, 2005), but becomes hard to distinguish from the above Altar Mountain Formation south of the Asgard Range (McKelvey *et al.*, 1977). In the Nibelungen Valley, the Odin Arkose consists of a pebbly sandstone or sandy conglomerate up to 5m in thickness (McKelvey *et al.*1977)

Paleoenvironmental interpretations range from low sinuosity streams (Barrett and Kohn, 1975) to a shallow marine environment (Bradshaw, 1981; Gilmer, 2007). Bradshaw (1981) suggests that the presence of *Skolithos* trace fossils within cross bedding indicates a shallow marine setting where the sand has greater cohesion.

2.5 Summary of Depositional Settings

The basement rocks in southern Victoria Land are predominantly composed of metasedimentary rocks that are regionally intruded by plutons of Cambrian to Ordovician granite Harbour Intrusives. The Koettilitz Group represents the metasedimentary basement in the field area in this study. The regionally extensive Kukri Erosion Surface truncates the basement geology with significant lateral changes in its topography. The Kukri Erosion Surface is then overlain with the Devonian age (?) Beacon Supergroup, in particular the Taylor Group, which consists of extensively cross bedded arkosic to quartzose sandstone and dark, ripples siltstone sequences.

The Taylor Group sedimentary sequences consists of 7 formations, from oldest to youngest, these are; the Windy Gully Sandstone, Terra Cotta Siltstone, New Mountain Sandstone, Altar Mountain Formation (Odin Arkose Member), Arena Sandstone, Beacon Heights Orthoquartzite and the Aztec Siltstone. For clarification, the formations from the Windy Gully Sandstone to the Odin Arkose Member of the Altar Mountain Formation are those included in this study but no younger.

These formations have a range of proposed paleoenvironmental interpretations. Figure 2.3 summarizes depositional settings from previous authors of the Taylor Group (lower Beacon Supergroup) and shows the diversity of differing opinions of particular depositional environments. The New Mountain Sandstone in particular has a number of paleoenvironmental interpretations ranging from subaqueous to subaerial.

Author	Windy Gully Formation	Terra Cotta Formation	New Mountain Formation	Boreas Subgreywacke Member	Plane Table Member	Altar Mountian Formation	Odin Arkose Member	Arena Formation
Harrington and Speden (1962)	Mostly marine with some lower beds maybe estuarine or non-marine							
Barrett and Kohn (1975)	-	-	Shallow marine. Large sand waves.	-	-	Non-marine, possible coastal environment	Low sinuosity streams	Alluvial plain deposit
Barrett (1979)	-	Lacustrine	Aeolian	-	-	-	-	-
Bradshaw (1981)	Tidally active marine environment. Shallow marine	Coastal lagoon	Shallow marine	Debris flow	-	Shallow marine	Shallow Marine	Low gradient sand plain with periodic flooding
Plume (1982)	Large braided fluvial streams, aeolian origin for some cross beds	Lacustrine	Non-marine. Aeolian and/or sandy braided river.	Alluvial fan	Lacustrine	-	-	-
Woolfe (1990)	Non-marine based on trace fossils.							
Turnbull *et al* (1994)	-	-	Fluvial	-	-	-	-	-
Wizevich (1997)	-	-	Fluvial-Aeolian	-	-	-	-	-

Figure 2.3 Summary of depositional settings for formations and members within the Taylor Group; lower Beacon Supergroup (variation of Gilmer, 2008)

3. Chapter 3- Geological Units – Observed and Discussed

3.1 Introduction

This chapter describes, analyses and discusses the formations studied throughout the field area. Members and formations along the stratigraphic sections have been subdivided into lithofacies to track lateral variation and interpret environmental changes throughout. For consistency, a selection of the lithofacies, if related, will coincide as much as possible with Gilmer (2007) and Savage (2005). This is to aid in correlation to field areas with close proximity to that of the author.

3.2 Kukri Erosion Surface and Windy Gully Basal Conglomerate Lithofacies

3.2.1 Introduction

The Kukri Erosion Surface, previously referred to as the Kukri Peneplain (Gunn & Warren, 1962), is a wide spread basal nonconformity to angular unconformity that extends throughout much of the Transantarctic Mountains and in particular, Southern Victoria Land. The erosion surface truncates the crystalline basement and separates the basement rock from the overlying Beacon Supergroup (Gunn & Warren, 1962; Grindley, 1963; Skinner, 1965; McKelvey *et al.* 1977; Plume, 1978; Anderson, 1979; McElroy & Rose, 1987; Barrett, 1991; Isbell, 2004)

The condition of the KES varies greatly over short distances from fresh, clean swept basement with little or no rubble to extensive rubble surfaces and highly weathered basement. This range of characteristics gives insight to particular paleoenvironments. The KES was not seen at all locations, but in those where it was present it shows a number of different scenarios that formed the erosion surface.

During this research the Kukri Erosion Surface was observed at the Nibelungen Valley and New Mountain (Windy Gully) field sites but was not seen in the following locations; Folkvanger Valley, Knobhead (Handsley Valley) and Rotunda

3.3 Erosion Surface Variation by Location

The Kukri Erosion Surface (KES) and the overlying rubble surface, the 'Windy Gully Basal Conglomerate Lithofacies' (see in depth in chapter 4), vary greatly in their relationship and the author suggests that from what was seen in the field is due to topographical changes and environmental relationships.

In this section the Basal Conglomerate Lithofacies of the Windy Gully Sandstone (WG-BCL) will also be mentioned and described as it directly overlies the KES.

3.3a Nibelungen Valley

The Kukri Erosion Surface in this area was seen in numerous locations but was often inaccessible. Just north-west of the Nibelungen base camp the exposure of the KES was seen from a distance so photos and approximate measurements were taken. It showed a rubble horizon up to 2m thick with sub-rounded to rounded boulders up to 1m in diameter. These boulders were incorporated into the WGSst above (The Windy Gully Basal Conglomerate Lithofacies) seen in Figure 3.1.

Figure 3.1 The Kukri Erosion Surface in Nibelungen Valley with close up of Windy Gully Basal Conglomerate, and Interfingered Siltstone and Cross Bedded Sandstone Lithofacies, Nibelungen Valley

Other basal contact exposures north of base camp were also observed; they range from highly weathered (figure 3.2) to fresh granite basement with no overlying rubble. The overlying sediments were of very weathered rubble texture with scattered pebble sized clasts of quartz and were very dark green/grey coarse, poorly sorted, angular quartz sandstone with deteriorated feldspar grains throughout.

Figure 3.2 Weathered basement contact north of base camp with Taylor sediments infiltrated, Nibelungen Valley

South of base camp the KES is largely obscured by scree slopes and is very close to extensive dolerite sills. The contact at this location is very irregular and the basement rock is of porphyritic texture with large alkalai feldspar crystals. Here the KES has little or no rubble horizon and appears to be relatively clean swept.

At this location an assessment of the KES topography shows a northward apparent dip and the boulder sized clasts in the directly overlying Windy Gully Basal Conglomerate Lithofacies (see chapter 4) indicates a high energy environment. The highly weathered basement profile south of camp indicates a lower energy environment but with sustained chemical erosion; this could suggest the development of a soil horizon away from the high energy environment slightly further north.

3.3b Windy Gully

The time spent at Windy Gully paid particular attention to the Kukri Erosion Surface due to good exposure at the base of the stratigraphic section. This particular site provided a number of exciting features in a confined area and gave insight into the distinct variability of the KES's characteristics. Well exposed crystalline igneous basement rock was seen at the base of the section with clear contacts with the overlying Windy Gully Sandstone (described before by Zeller *et al.* 1961 in this location). The extreme range in topography of the KES results in a variable thickness of the Windy Gully Sandstone and Terra Cotta Siltstone Formation before large diorite sills intruded the section for more than 200m (See figure 3.3). The KES varies locally in topography by up to 30m in height and shows a large range of clast sizes preserved as the Windy Gully Basal Conglomerate Lithofacies.

The most prominent features in this location are the two large 30m+ topographical highs in the KES, one almost protruding the full stratigraphic height of the Windy Gully Sandstone Unit. For formality, the two topographical highs will be named TH1 and TH2 (see figure 3.3).

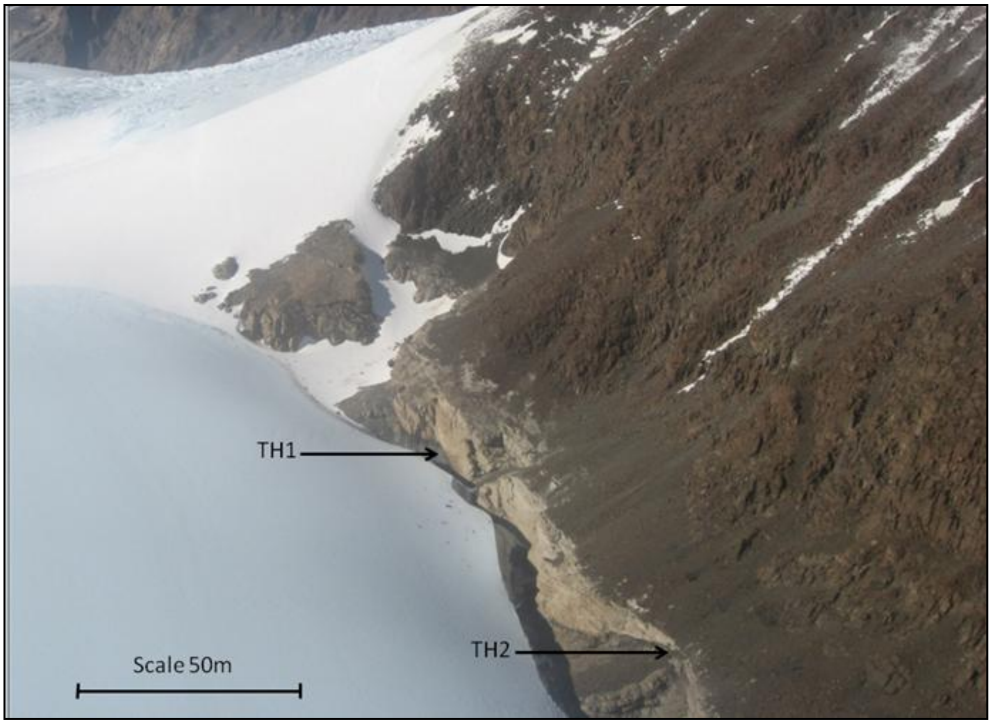

Figure 3.3 Aerial view looking down at the Kukri Erosion Surface at Windy Gully, TH1 and TH2 point out relative topographical highs in the Kukri Erosion Surface

The first topographical high (TH1) has a rounded top, a thin rubble layer and a highly weathered basement horizon (Figure 3.4) with about 5-15m of Windy Gully Sandstone above. The second topographical high (TH2) comes to an abrupt point (projecting almost the full thickness of the WGSst) and has thick rubble layers down the southern flank and a clean swept point. TH2 also has meter-scale cross bedded quartzose sandstones onlapping either side in the upper reaches as it interacts with the range of the Windy Gully Lithofacies. Lying conformably above the sandstone is a thin section of the stratgraphically higher Terra Cotta Siltstone but it is partially cut off by a dolerite sill.

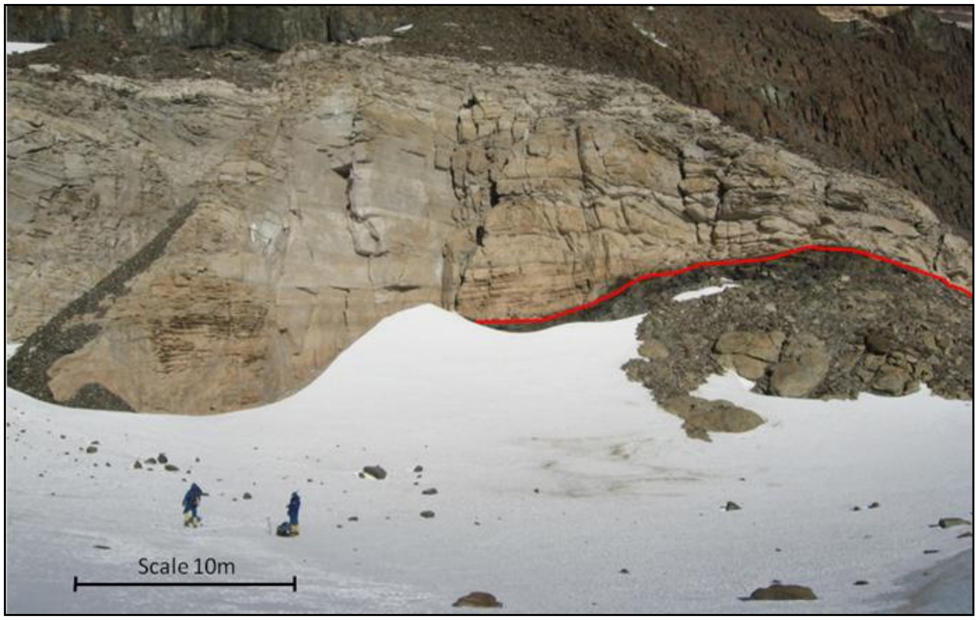

Figure 3.4 First topographical High (TH1) of the KES at Windy Gully site

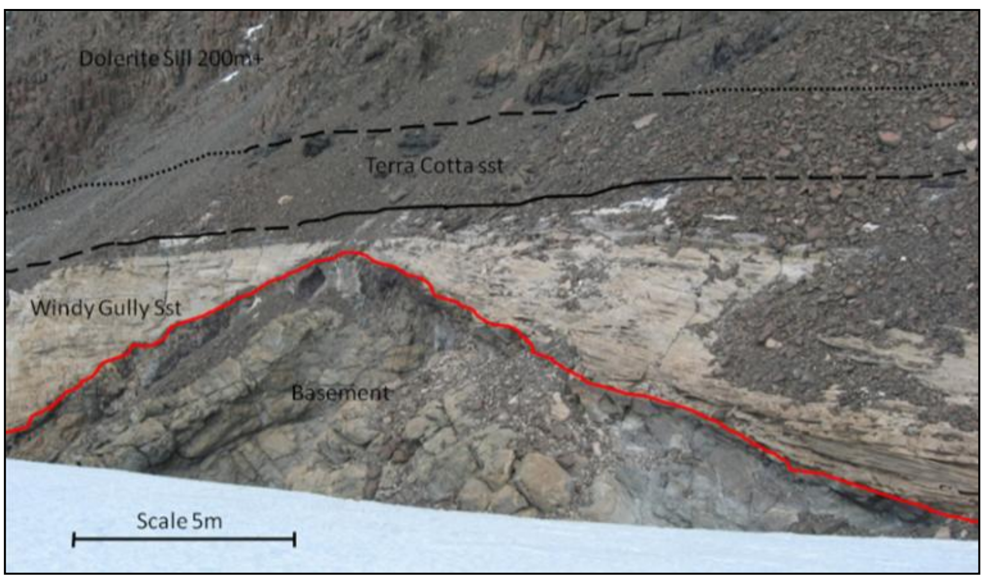

Figure 3.5 Topographical high of the Kukri Erosion Surface observed at Windy Gully. Note that the feature projects below the glacier horizon

Closer inspection of the outcrop TH2 shows a number of small scale features that, although being very different laterally, give insight to the depositional setting after the KES was exposed.

Inspection of the southern flank of TH1 reveals a thin ~10cm horizon of angular rubble covering highly weathered crystalline basement with a 5cm horizon. Observed along the horizon were compression type structures in the weathered basement foliation (figure 3.6 A&B). This suggests chemical weathering resulting in friability of the basement at the time of exposure. This horizon is interesting as other sections of the basement are swept clean before further deposition took place.

Figure 3.6 A&B Close view, from front and obliquely, of KES showing compression in foliation at location TH1, Windy Gully

In contrast, a clean swept surface has been formed on the north dipping flank of TH1. It has rare lithic clasts that lie directly on the KES surface and appear to be fragments of basement (see figure 3.8A). Most of the clasts are sub-angular and are also seen scattered in the overlying WGSst directly above the swept surface (figure 3.7 B&C). The author suggests a flat lying, high energy environment with a lack of sediment supply (in terms of rubble seen at

TH2) and the geometry of the feature allowed it to be swept entirely clean. This could be due an exposed face constantly being swept clean.

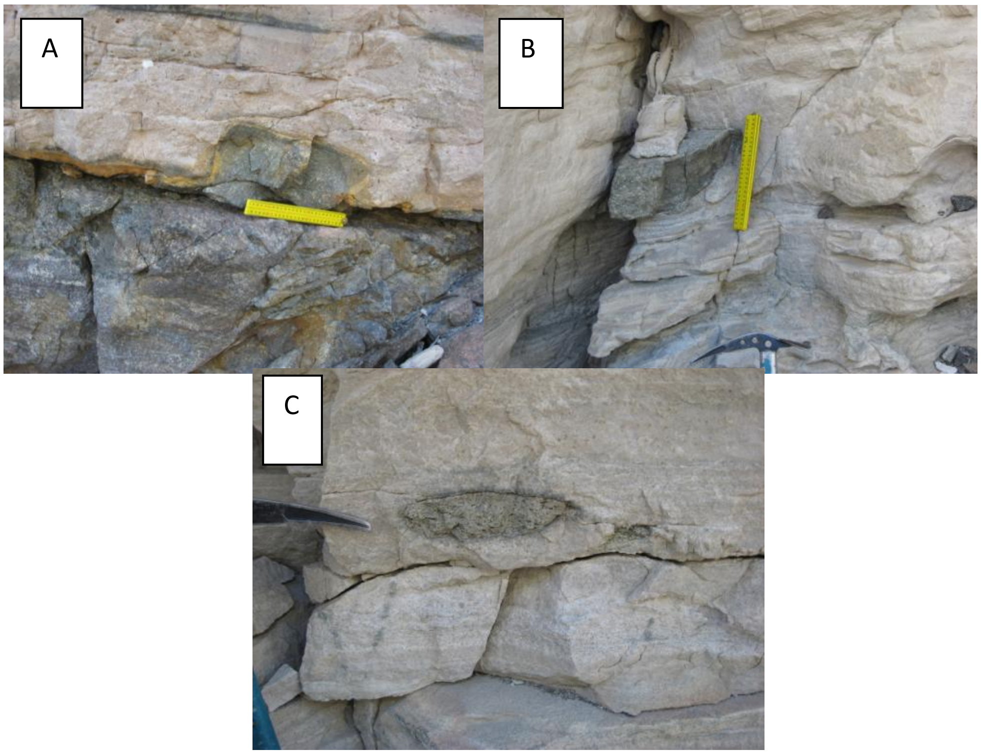

Figure 3.7 A, B&C Clasts of basement deposited directly on the KES and within close stratigraphic proximity in the above WGSst, Windy Gully

TH2, however, displays different characteristics. It has an abrupt peak and a higher angled face (20-30°) yet is only ~50 meters away from TH1. This indicates a much higher energy environment seen in terms of grain size, roundness of grains and interaction with overlying units.

The grain size of the basal conglomerate clasts is no less than cobble and is commonly boulder size. The angularity of clasts ranges from very angular to well rounded but is predominantly well rounded in the upper parts with angular clasts being confined to the base against the KES.

Along the extent of TH2, in the Windy Gully area, a selection of other features were observed. These include angular boulder slip or fall deposits with weathering rinds and cavity infilling/sediment trap. These are referred to as the Windy Gully Basal Conglomerate Lithofacies (WG-BCL) but provide insight to the KES environment and are therefore included.

An outstanding feature on TH2 is the thick angular to sub-angular rubble deposit consisting almost entirely of basement rock. Seen in figure 3.9, the red line indicates the KES and the yellow indicates the top surface of the boulder deposit (and also outlining the void/sediment trap). The rubble layer is approximately 6.5m thick, appears to be of slightly reverse grades, and a number of the boulders contain weathering rinds. This horizon has been incorporated as the WG-BCL as it is depositional by origin.

This deposit proves difficult to decipher as no source can be seen locally and the topography of the KES at this location is too shallow to produce such a deposit. A suggested source could be some sort of local cliff structure or extreme change in topography and the resultant deposit is a preservation of slip/fall events. The author suggests that subsequent slip events were reworked by wave action that enabled weathering, including rounding of boulders and weathering rings. If the topography is so variable at this location then it is possible that there would be such a source close by that is not seen. The weathering rings can be seen in both the infill clasts and particularly in the deeper slip/rockfall deposit (see figure 3.8 towards the bottom left and where Dr. J. Bradshaw is pointing).

In addition, another significant feature, as mentioned, was the large cavity structure and thick rubble surface infilling along the slope of TH2 (figure 3.8). The cavity is filled with angular to sub-rounded cobble to boulder sized basement rock with a matrix of medium to coarse quartzose sandstone from the overlying sandy facies of the WGsst. This infilling shows a generally smaller grain size with less rounding than what has been seen along the KES elsewhere. This feature has acted as a trap for sediment and gives better insight to the range of grain type and size on the KES. The cavity/sediment trap most likely exists due to the extreme size of the original rubble deposit and spaces in between boulders. The filling of this cavity with conglomeratic sediment and quartzose Windy Gully sediment was therefore deposited soon after the initiation of deposition.

Figure 3.8 Rubble filled cavity along slope of TH2, Windy Gully. John Bradshaw as a scale

3.4 Discussion and Interpretations

The KES was seen extensively and well exposed in two of the field areas, the Nibelungen (inaccessible) and New Mountain (Windy Gully), and in both shows variation in characteristics over relatively small distances. The topography in both sites range well over 5 m in relief and dips at least 10°. Weathering along the KES also ranges greatly depending on the topography, for example, the two topographical highs seen in Windy Gully (TH1 and TH2) and their associated topographical lows.

The relief of the KES has previously interpreted as the result of a karstification process aided with irregularities and topography regardless of relief (Isbell, 1999). The variation of weathering along the outcrops suggests areas of prolonged exposure and in places swept clean by physical processes. The author agrees and suggests that the KES represents a high energy rocky shore face environment similar to what is seen nowadays on the West Coast, New Zealand (see example figure 3.9) and the differences in weathering and erosional product would be dependent on the orientation to the shore face and interaction with the high energy environment. The deep weathering of the basement rock also suggests an extended period of non deposition and in cases, non erosion. This again would be dependent on the orientation of the KES to the erosional processes. Deposition after erosion would have initiated in topographical lows and formed the basal conglomerates mixed with the initiation of beacon sediments, in this case the Windy Gully feldspathic quartz sandstone.

The author interprets the KES paleoenvironment as a rocky shoreline, produced by exhumation of the Ross orogenic belt (Isbell, 1999). This was the result of intense prolonged weathering and formed high relief topography due to karstification processes of a possibly already high relief inherent body. Continued erosion of the high relief body resulted most likely in sea stack formations and a continuous supply of basement rubble, explaining the variety of roundness of clasts in the WG-BCL. This is seen in the Windy Gully in figure 3.8 where the WG-BCL has syndepositional rubble and feldsarenite sandstones.

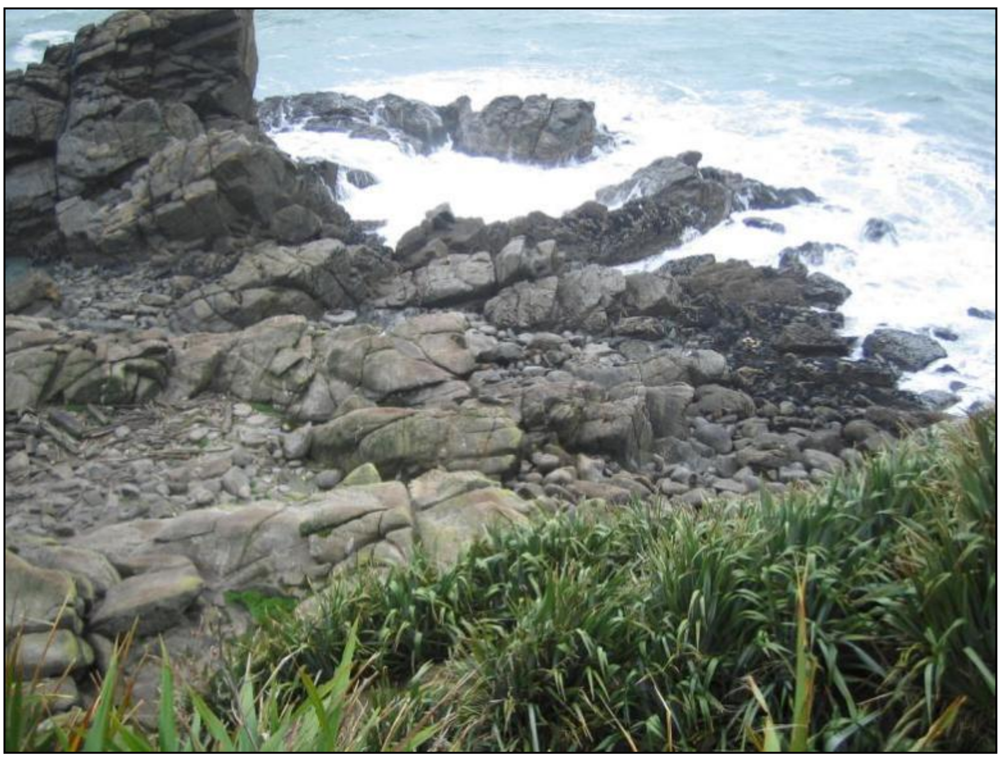

Figure 3.9 Existing shore face example of granitic basement composition and high topography from extended erosion, Cape Fowlwind, West Coast, New Zealand. Note the accumulation areas in topographical lows.

3.5 Conclusions

The Kukri Erosion Surface represents the exhumation of the Ross orogenic belt forming a high energy erosional contact. The author suggests that the Kukri Erosion Surface represents a rocky to smooth swept shore face that sustained prolonged erosion with a high range in topography on granite basement rock similar to that seen on the West Coast, New Zealand. The topography was the result of extensive karstification processes and a remnant of the original relief. A relative sea level rise initiated deposition of the WGSst sediments and syndepositional relationships with remaining basement rubble and introduced feldspathic quartz sediments forming the Windy Gully Basal Conglomerate Lithofacies.

4. Chapter 4 - Windy Gully Sandstone Formation

4.1 Introduction

The Windy Gully Sandstone Formation (WGSst) is the lowest unit in the Taylor Group and is bound between the basal Kukri Erosion Surface (KES) and the overlying Terra Cotta Siltstone (TCzst). It contains predominantly moderately to well sorted, cross bedded, subfeldsarenite successions with trace fossil assemblages throughout. It becomes gradually less feldspathic and finer grained towards the top. The WGSst throughout the field is relatively consistent varying only in thickness due to relief on the KES.

The WGSst was observed in all locations where the Kukri Erosion Surface was seen but poor exposure, accessibility issues and dolerite sill intrusion made accurate measuring and recording difficult in places. This resulted in partial sections, observations made from a distance and many measurements made by handheld GPS. The Windy Gully Sandstone was not observed in the following areas; Mt Boreas, Folkvanger and Rotunda?

4.2 Lithofacies

The WGSst has been divided into lithofacies to aid interpretation of specific depositional conditions, enable comparison with other formations, and to clarify patterns of how depositional environments change through the progression of deposition. This will later be compared with sequence stratigraphy to show the progression of depositional and environmental conditions. The lithofacies of the Windy Gully Sandstone are described from the base moving upward and are based on grain size, sedimentary structures and trace fossil assemblages.

4.2a Windy Gully Basal Conglomerate Lithofacies (WG-BCL)

The WG-BCL is in basal contact with the Kukri Erosion Surface. It varies in thickness from absent, where the KES has been swept clean, to a clast supported cobble to boulder conglomerate with a matrix of medium to coarse feldsarenite. Thick boulder sized rubble horizons of the WG-conglomerate show a large variation of clast size, roundness and composition.

The range in thickness varies considerably over short distances and appears to have a direct correlation with relief on the KES. The very thin to nonexistent sections of the WG-BCL occur on topographic highs of the KES which are instead overlain by the Windy Gully Granule Cross Bedded Sandstone Lithofacies (WG-GCL) and in one instance, the Windy Gully Tabular or Trough Cross Bedded Sandstone Lithofacies (WG-CSL). The thickest conglomerates occur in topographic lows that appear to be acting as catchment areas. The conglomerate is both clast and matrix supported depending on the association with KES the relief

The WG-BCL is other basal conglomerates observed in the field are comparable, for example, the New Mountain Sandstone and Altar Mountain Formation Basal Conglomerate Lithofacies (see Chapter 7&9) in terms of the presence of preserved fragments of the basal product.

4.2b Windy Gully Granule Cross Bedded Lithofacies (WG-GCL)

The Windy Gully GCL has a lower contact with the KES or the WG-BCL and an upper contact with the WG-ICSL or the WG-Tabular CSL. It consists of moderate to poorly sorted, low angle tabular to slightly trough cross bedded medium to coarse feldsarenite. The feldspar occurs throughout but coarse grains are often concentrated along the cross bed foresets. The cross beds are 0.5-1.5m thick and have rare and scattered trace fossil assemblages. Note that the WG-GCL was dependent on the lack of conglomerate clasts; if clasts of basement were present then it was classified as the WG-BCL.

4.2c Windy Gully Interbedded Siltstone and Cross Bedded Sandstone Lithofacies (WG-IZCL)

This lithofacies was only seen in the Nibelungen Valley and consisted of thin 10-30cm thick, dark very fine sometimes rippled sandstone to siltstone horizons (similar to that of the Terra Cotta Siltstone Formation) interbedded with well sorted, low angle tabular cross bedded fine to medium sand subfeldsarenites.

4.2d Windy Gully Low Angle Tabular Cross Bedded Sandstone Lithofacies (WG-Tabular CSL)

The WG-Tabular CSL occurs twice in the WGSst. It appears below and above the WG-Tabular CSL and as the uppermost lithofacies of the WGSst meeting gradationally with the Terra Cotta Siltstone Formation. The lower WG-Tabular CSL is bound at its base by the KES, the WG-GCL or the WG-ICSL and the upper WG-Tabular CSL is bound at its base by the WG-Trough CSL and at its top by the gradational contact with the Terra Cotta Sandstone Formation (TCzst). The concentration of feldspar does differ between the two lithofacies as the WGSst gradually decreases in feldspathic content from base to top. The WG- Tabular CSL is divided into the upper and lower due to the separation by the WG-Trough CSL and differing trace fossil assemblages, *Heimdallia* dominant in the lower and *Skolithos* dominant in the upper.

4.2e Windy Gully High Angle Trough Cross Bedded Sandstone Lithofacies (WG-Trough CSL)

The WG-Trough CSL consists of higher angle trough cross beds (between the upper and lower Low Angle Tabular Cross Bedded Sandstone Lithofacies). The cross beds consist of medium to well sorted medium sand subfeldsarenites. Trace fossils in this lithofacies are sparser than in the upper and lower WG-Tabular CSL but exist in sporadic horizons.

4.3 Facies Distribution and Relationships in Observed Sections

Each locality where the Windy Gully Sandstone was observed will be presented in detail below. Relevant measured sections can be found in appendix A1. Measured sections will be described in terms of the lithofacies defined above with some additional information specific to the locality.

4.3a Nibelungen Valley

The Nibelungen Valley (Figure 1.3, locality map) proved difficult to measure due to accessibility problems but was well exposed in the upper reaches. The lower sections were seen from a distance and notes were taken particularly in terms of the relationship with the Kukri Erosion Surface, the Basal Conglomerate Lithofacies (WG-BCL) and the Interbedded Siltstone and Cross bedded Sandstone Lithofacies (WG-IZCL). Further up in the succession the upper Low Angle Tabular Cross Bedded Sandstone Lithofacies (WG-Tabular CSL) was also present between the WG-IZCL and the upper contact with the gradational Terra Cotta Contact.

The best exposure of the WG-BCL was only able to be viewed from a distance due to accessibility issues but gave insight to the depositional environment and interaction with the Kukri Erosion Surface, described in Chapter 3. Exposure of the KES is seen elsewhere but the WG-BCL is poor and often obscured. The Basal Conglomerate Lithofacies (WG-BCL) range between an estimated 0-2m thick but scattered conglomerate clasts are seen up to 5m into the cross bedded sandstones. The WG-BCL consists of massive to very low angled tabular cross bedded sandstone matrix and sub angular to sub rounded basement cobble and boulder clasts. Elsewhere in the area the WG-BCL consists of weathered basement and is observed to be on a topographically higher portion of the KES (see figure 4.2)

The WG-BCL seen from a distance is clast supported at its base and progressively becomes matrix supported as clasts are seen scattered along cross bed foresets (see figure 4.1). It is suggested that the matrix supported horizons are therefore a product of subsequent debris flows and that the clast supported basal portion represents the rubble deposited directly after erosion ceased. The separated horizons of the WG-BCL suggest that the conglomerate clasts were being periodically fed into the system during deposition. The conglomerate clasts also show a degree of imbrication providing an estimated dominant paleoflow direction towards the south. The author suggests that the presence of intermittent boulder horizons also suggests a degree of high relief of the KES in the area providing a feasible source.

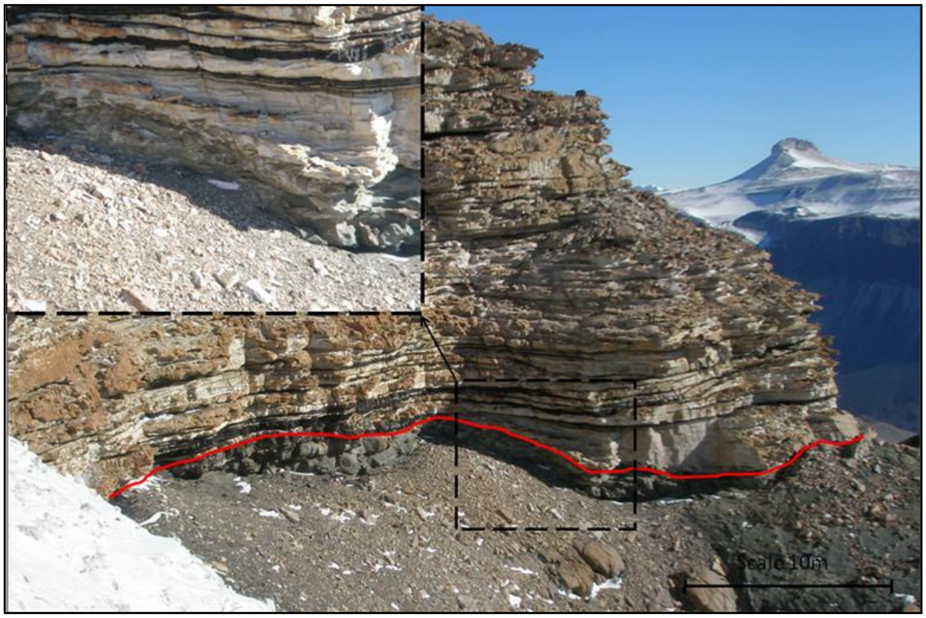

Figure 4.1 Close up of Windy Gully Basal Conglomerate and Interfingered Siltstone and Cross Bedded Sandstone Lithofacies directly overlying the KES, Nibelungen Valley

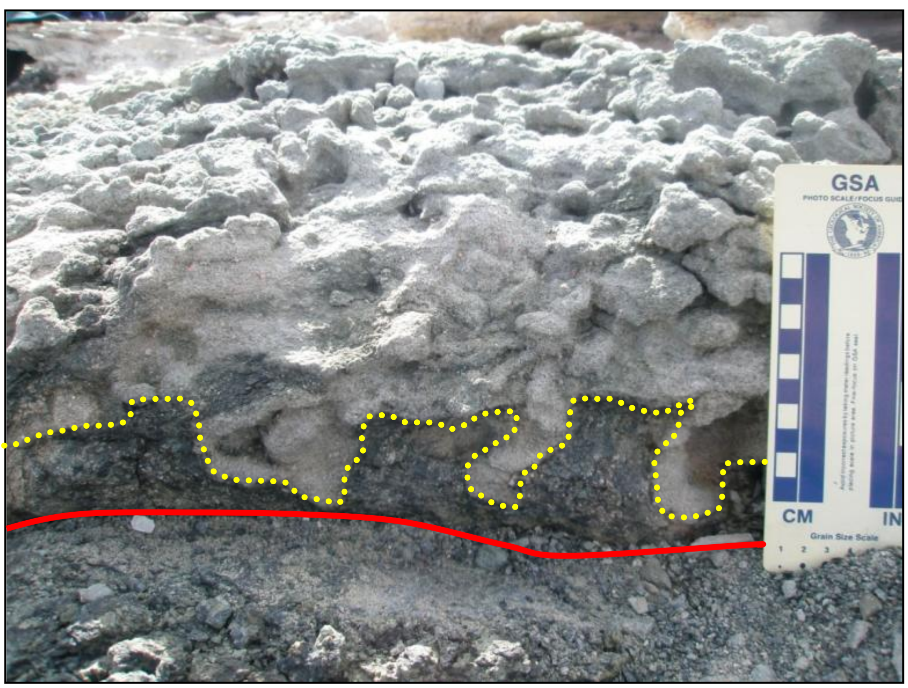

Figure 4.2 Windy Gully Basal Conglomerate Lithofacies directly overlying the KES (red) with Taylor sediments infiltrated (yellow), Nibelungen Valley

Areas where the KES slopes more than approximately 15° or appears to be topographically high, the WG-BCL thins dramatically and is substituted with onlapping low angle cross beds. The WG-BCL conglomerate is subangular to subrounded suggesting a degree of high energy reworking.

The WG-IZCL directly overlies the WG-BCL and is only seen in this area. It consists of interbedded thin brown-black siltstone horizons similar to that of the Terra Cotta Siltstone Formation. The siltstone horizons are interbedded with low angle tabular cross bedded quartz medium sands subfeldsarenites. The WG-IZCL lay stratagraphically above the WG-BCL and appears to be over 20m thick in places before progressing into the Low Angle Tabular Cross Bedded Sandstone Lithofacies (WG-Tabular CSL). Because the WG-IZCL could not be observed up close, any evidence of trace fossils was not able to be described.

The measured section starts with the WGSst (Appendix A1). It consists of ~6m of interbedded massive beds entirely bioturbated by *Heimdallia* with very low angle tabular cross beds and massive subfeldsarenite sandstones. The lower WG-Tabular CSL lithofacies consists of massive beds of entirely bioturbated with Heimdallia between very low angle cross beds and massive subfeldsarenites. In many cases the Heimdallia bioturbation horizons cut into the below cross beds. Coarse to very coarse sand grains of both feldspar and quartz are preserved along cross bed foresets indicating reworking of grains.

Trace fossils in the Windy Gully Sandstone consist predominantly of *Heimdallia* in the upper WG-Tabular CSL upper regions where the sediments are trending more towards well sorted fine to medium sandstone.

4.3.3b Knobhead (Handsley Valley)

Exposure in the Handsley Valley is mostly poor resulting in only 2m of the upper WGSst being measured (Figure 1.6 locality map, appendix A1 strat 12).

The measured section of the WGSst consists of the WG-Tabular CSL with white, very well sorted, low angle cross bedded, *Heimdallia* bioturbated quartz sandstone (see figure 4.3). *Skolithos* is absent and continues directly in a gradational contact to the overlying Terra Cotta Siltstone (TCzst). The gradational contact is over 1m of low angle cross bedded fine quartzarenites interbedded with pale green, very fine fissile sand to siltstone. This is described in the TCzst section.

Figure 4.3 *Heimdallia* trace fossil in WGsst, Knobhead (Handsley Valley)

4.3c New Mountain (Windy Gully)

At the New Mountain location the entire thickness of the WGSst was seen from the basal contact (KES) to the Terra Cotta Siltstone (TCzst) (Figure 1.7 locality map; appendix A1 New Mountain).

Immediately overlying the KES is the WG-Basal Conglomerate Lithofacies which varies in thickness from nonexistent to 6.5m thick. This is in turn overlain by both the upper and lower trough, and tabular WG-CSL, due to the high KES relief. The Kukri Erosion Surface (KES, chapter 3) has a very dramatic topography and this is reflected in the thickness of the WG-BCL and its overlying facies association. A noted feature is the thinning over KES topographical highs (TH1 & TH2, see chapter 3) and a thickening within the troughs and the rugged topography of the flanks. At the peaks of the topographical highs the WG-BCL is nonexistent or consists of single clast thickness before proceeding directly into the WG-CSL.

The WG Basal Conglomerate ranges from clast supported rubble to matrix supported conglomerate to very poorly sorted pebbly sandstone. Clast sizes range from pebble to large boulder and roundness from angular to well rounded (see figure 4.4). The roundness varies in relation to the clast size, becoming more rounded as clast size decreases. The composition of the clasts consists almost entirely of local granitic basement.

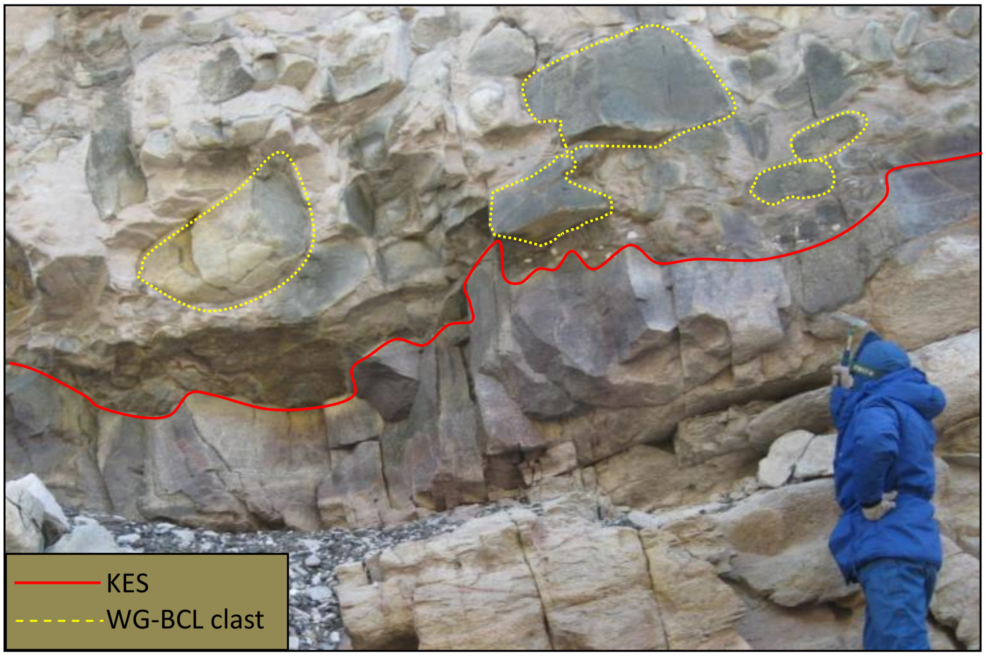

Figure 4.4 view of the WG-BCL bound at its base by the KES showing the range of roundness, from sub angular to well rounded, granitic basement clasts bound within moderately to well sorted feldspathic quartz sandstone, New Mountain (Windy Gully)

The thickest WG-BCL occurs along the flanks of the topographical highs. Angular rubble horizons are up to 5m thick and have very little quartzose matrix. The clasts in the rubble horizons show thick weathering rinds (see figure 4.5).

Figure 4.5 Weathering rings of two individual WG-BCL clasts on the KES, New Mountain (Windy Gully)

The NM-BCL horizons entirely composed of basement rock consisted of pebble to cobble conglomerate with poorly cross bedded feldspathic quartz sandstone. A majority of the clasts were randomly orientated due to their shape but clasts that had elongation commonly showed a degree of imbrication. This aided with the degree of rounding of the basal clasts and evidence of cross bedding indicates sufficient reworking of the clasts and deposition within the active environment. Scattered angular basement clasts were also randomly seen throughout the conglomerate indicating sporadic periods in which the clasts were fed. The author suggests that the source would have to be proximal to the location of deposition to show such angularity and that the topography of the basement and KES supports this.

The WG-GCL in this area was only really present for 30cm above the finer grained WG-BCL clasts and consisted of moderately to poorly sorted granule low angle tabular cross bedded feldspathic quartzose sandstone. As seen elsewhere the coarser feldspar grains were concentrated to cross bed foresets.

A majority of the WG-Tabular/Trough CSL was seen from a distance due to accessibility issues but a clear view was able to show the variation in cross bedding throughout the lithofacies. The interaction of the highest topographical high (TH2, see chapter 3.2) sought that almost the entirety of the WG-Tabular/Trough CSL onlapped against it (see figure 4.6). A noted feature at this location was the interaction with the KES and the associated WG-BCL but mainly the onlapping relationship and progression of cross bed characteristics (see figure 4.6).

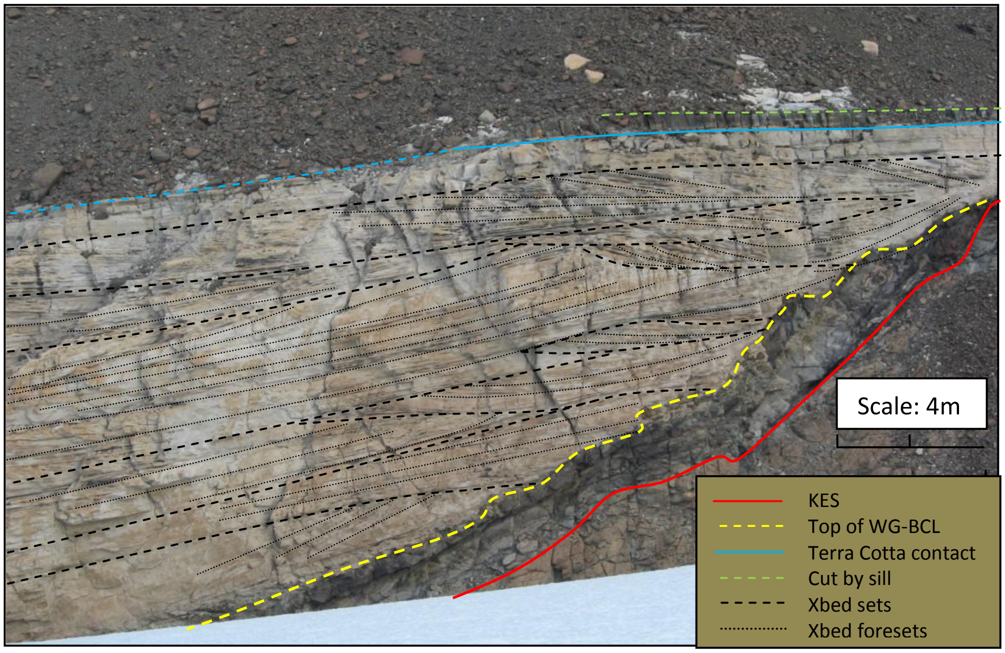

Figure 4.6 Cross bedded sandstones of the WG-CSL onlapping the basement southern flank of the topopgraphical high TH2, New Mountain.

The lower WG-Tabular CSL is ~6-8 m thick and is comprised of low angle tabular cross bedded feldsarenite sandstone. The middle WG-CSL trough cross bedded sandstone beds are only ~2 m thick and are not laterally continuous. The upper WG-CSL again consists of well sorted, low angle tabular cross bedded, medium quartz sandstones with a lesser feldspathic content than the lower WG-CSL. The upper WG-Tabular CSL is gradationally overlain by the Terra Cotta Siltstone.

Scattered bioturbation horizons by *Skolithos* trace fossils are present in the upper WG-CSL only and not in the lower or middle units (see figure 4.7). The *Skolithos* trace fossil assemblage appears to have a thicker form and look almost like the *Heimdallia* trace fossil burrows.

Figure 4.7 *Skolithos* and possibly *Heimdallia* trace fossil in the upper WG-Tabular CSL low angled tabular cross beds before the Terra Cotta Siltstone Formation gradational contact, New Mountain (Windy Gully)

4.4 Discussion and Interpretation of Depositional Settings

The Windy Gully Sandstone Formation has previously had two main interpretations; shallow marine (Bradshaw, 1981) and fluvial (Plume, 1982). The author challenges a fluvial scenario based on the following and interprets the WGSst as deposited in paralic to nearshore shallow marine environments.

The Windy Gully Sandstone Formation was seen in 3 locations, two of which had exposed and accessible outcrops of underlying KES. The WGSst varies in total thickness in direct correlation to the topography of the basement; it is at its thinnest on topographic highs and thickest along the flanks and in the troughs (see figure 4.6). The WGSst is thickest in the north and thinner in the south but this is based on only two locations (see figure 4.8). At the Knobhead location only the top of the WGSst was able to be measured hence the thickness measurement will not be included.

	Lithofacies Thickness (m)				
Location	WG-BCL	WG-IZCL	WG-GCL	WG-CSL	**Total**
Nibelungen Valley	2.0 -5.0	50	1.5	6	**60.5-62.5**
Knobhead (Handsley Valley)	Not seen	Not seen	Not seen	>2	**NA**
New Mountain (Windy Gully)	0-6.5	absent	0.3	2-15	**2-21.5**

Figure 4.8 Summary of the WGSst lithofacies thicknesses throughout the field, moving north to south

The Windy Gully Sandstone however is bound at its base by the Kukri Erosion Surface and has an extensive rubble horizon of granitic basal conglomerates (the WG-BCL). The conglomerates range in size angularity, roundness and progress from clast supported at the base to matrix supported moving into low angle cross bedded very coarse sand to granular subfeldsarenite sandstones .The majority of the Windy Gully Sandstone Formation is medium to fine cross bedded sandstone varying between low angle tabular cross stratification and trough cross bedding.

3.3.4a Windy Gully Sandstone Basal Conglomerate lithofacies

The Basal Conglomerate Lithofacies (WG-BCL) shows a range of weathering of clasts from angular to well rounded boulders and cobbles, some of which have weathering rinds. The author suggests that the rounding of clasts has a direct relation to the clast size and time of introduction. Directly above the KES at the New Mountain location, very large boulder deposits are present and up to 4m thick. The clasts involved are commonly between 1-4m in diameter and are predominantly angular and sometimes contain weathered rinds. The author suggests that this was the result of a rock fall or cliff face collapse on a rocky shore platform and that the topography was sufficient to provide such sediments. This can b seen both by intermittent influx of basement rock into the cross bedded sandstones and the thick rubble horizons along the flanks of the KES topographical highs.

Cobble to small boulder sized basement clasts were predominantly moderately to well rounded and clast supported and thus indicate a high energy environment, however rare angular clasts of the same size were also present. This is most likely due to sporadic introduction of clasts into the depositional prograding sediments of a developing beach environment and thus not being given sufficient time to erode to the same or similar degree to the other surrounding clasts that were reworked over a long period of time.

Smaller basal cobble to pebble clasts are observed within low angle tabular cross bedded sandstones and are almost entirely moderately to well rounded. Elongation of clasts provides a slight imbrication if the horizon is concentrated but otherwise lie flat. The author suggests that the finer basal clasts on low angle tabular cross beds indicate a low angle beach environment and that the imbrication lies at the same angle as the beach front.

The WG-BCL combined with the Kukri Erosion Surface characteristics (elaborated in Chapter 3) suggests that the Kukri erosion surface was a high relief shoreline of granitic basement very similar to what is seen on the West Coast, New Zealand today and the WG-BCL was the conglomerate lag that has been introduced throughout erosion and throughout the initiation of deposition. The extensive rubble horizons were therefore a product of prolonged weathering and sporadic introduction and source of clasts from the instability of the high relief topography with collapsing sea stacks.

3.3.4b The Windy Gully Granule Cross Bedded Lithofacies

The WG-GCL was only seen in the New Mountain (Windy Gully) location and consisted of a granular low angle cross bedded subfeldsarenite sandstone. The author speculates that it was also present in the Nibelungen Valley but access issues resulted in it not being seen. The units composition is the same as the matrix seen in the WG-BCL but with no conglomerate clasts. The coarseness of the lithofacies indicates either a closer source body or a lack of sustained reworking before deposition. The author therefore suggests that the WG-GCL is a low angle granular beach environment occurring once deposition started on the KES. The concentration of coarser feldspar grains along tabular low angle cross bed foresets indicates reworking and sorting of the feldspar minerals before deposition common on a beach setting nowadays.

3.3.4c The Windy Gully Interbedded Siltstone and Cross Bedded Lithofacies

The WG-ISCL was only seen in the north at the Nibelungen Valley site and measured at approximately 50m. It consisted of very regularly interbedded dark well laminated siltstone beds and low angle cross bedded sandstones. The thin siltstone beds are quite similar to the siltstones of the overlying Terra Cotta Siltstone Formation (TC-FDL) (see Chapter 5). This combination of features best fits a tidal flat, lagoon or estuarine depositional setting with changing tidal conditions recorded by alternating fine siltstones interbedded with cross bedded sandstones of migrating dunes.

The regularity of the silt beds between the cross bedded sandstones suggests a cyclic event, for example, tidal interaction. The author suggests that in the Nibelungen Valleys area, the WG-IZCL was most likely deposited in an interdeltaic, tidal flat or lagoon environment protected by low angle barrier beaches. Tidal flats have distinctive characteristics similar to estuarine deposits which include bimodal cross bedding, flaser bedding and repeated sand and mudflat successions. They can occur over hundreds of kilometers or locally when formed by bays or barrier island environments forming lagoons or bays (Klein,1985). Mixed mud and sand horizons characterize the middle tidal zone where lower and supra-tidal environments meet resulting in repeating successions. An example of this is seen in late Precambrian beach sediments, Nevada (Klein, 1985). The author therefore determines the WG-IZCL as a locally occurring tidal flat environment, and according to Walter's law, protected by the low angle beach deposits following in the WG-Tabular CSL.

3.3.4d The Windy Gully upper and lower tabular Cross Bedded Sandstone Lithofacies

The WG-Tabular/Trough CSL was seen in its entirety in both the Nibelungen Valley and New Mountain (Windy Gully) sites and partially in the Knobhead (Handsley Valley) site. The cross bed successions progress from low angular tabular to higher angle trough and back to low angle tabular. The lower WG-Tabular CSL appears to be almost free of bioturbation horizons most likely due to the overall coarser grain size and consisted predominantly of very low angle tabular cross beds suggesting a beach setting. The NM-Trough CSL was at its thinnest in the Windy Gully consisting only of single trough cross bed sets indicating a deepening of the water column into shallow marine with channels forming for only a short period. The upper WG-Tabular CSL quickly moves back into a low angle tabular cross bedded beach setting but instead with *Skolithos* and scattered *Heimdallia* trace fossils. The whole WG-CSL gradually fined upward from base to top from a coarse sand to a more fine to medium sand. Feldspar content gradually decreased throughout. The author therefore suggests that the presence of the trace fossils indicate that the finer grain size in the upper WG-Tabular CSL beach setting was more favorable for living conditions than the coarser Lower WG-Tabular CSL as it was lower energy. The author also suggests that the WGSst did not reach subaerial aeolian dune deposits but moved from a low angle beach barriers resulting in localized tidal flat environments of the WG-IZCL in the Nibelungen valley.

In summary the lower WG-Tabular CSL represents a beach environment, the WG-Trough CSL represents a short lived deepening in the water column and therefore shallow and channelized marine environment and the upper WG-Tabular CSL represents a shallowing of the water column back to a beach environment.

4.5 Conclusions

The Windy Gully Sandstone has a basal conglomerate lying directly on the Kukri Erosion Surface but is comprised predominantly of cross bedded, fine to medium subfeldsarenite sandstones and represents a paralic to shallow marine environment. This has been concluded as changes in cross bed types and angles moving from low angle tabular, to higher angle trough and back into low angle tabular cross beds represents a progression from beach environments to; a deepening of the water column to shallow marine environments; and shallowing of the water column back to beach sediments. The author also suggests that the WGSst did not reach subaerial aeolian dune deposits but moved from a low angle beach barriers resulting in localized tidal flat environments of the WG-IZCL in the Nibelungen valley. The WGSst decreases in both feldspathic content and in grain size from base to top, indicating progressive weathering out of the feldspar content.

The presence of trace fossils in the uppermost WG-Tabular CSL indicate that the trace fossil *Skolithos* most likely favors a medium to fine sandstone beach deposit environment and is grain size dependent as it is not seen in finer or coarser sediments of the same depositional features. The trace fossil *Heimdallia* however exists also in the finer sediments suggesting that it is not grain size dependent in finer sediments.

5. Chapter 5 - Terra Cotta Siltstone Formation

5.1 Introduction

The Terra Cotta Siltstone Formation (TCzst) is bound between the Windy Gully Sandstone below and the New Mountain Sandstone above. The TCzst has a gradational lower contact over tens of with the Windy Gully Sandstone. Its upper contact is sharp in some places and erosional in others. The erosional surface is seen in places by scattered rip-up clasts and cross beds cutting into the unit in some locations and was disputably named the ‘Windy Gully Erosion Surface (Harrington, 1965). The erosional contact was disputed as it was not seen regionally but it provides a valuable insight into the depositional transition (see Chapter 6). Note that the TCzst was not included in all sites due to the start/finish point of sections relative to the Heimdall Erosion Surface and exposure of the outcrops.

The Terra Cotta Siltstone Formation was not observed in the following areas; Mt Boreas, Folkvanger and Rotunda

5.2 Lithofacies

The TCzst has been divided into two lithofacies, Sandy-Mottled (TC-SML) and Fissile-Dark Lithofacies (TC-FDL). The division represents physical and compositional characteristics that will aid in environmental interpretations.

5.2a Terra Cotta Siltstone Sandy Mottled Lithofacies (TC-SML)

The Sandy-Mottled Lithofacies has a gradational relationship with the underlying Windy Gully Sandstone; most commonly the upper Cross Bedded Sandstone Lithofacies (upper WG-CSL) or the Bioturbated Cross Bedded Sandstone Lithofacies (WG-BCSL). The TC-SML is usually the thinner of the two lithofacies and contains grey to khaki green fissile, well laminated very fine quartz sandstone with scattered well rounded quartz granules and sometimes rare pebbles at its base. Small asymmetric ripples and desiccation cracks are commonly observed but often showing compression structures making identification difficult.

5.2b Terra Cotta Fissile Dark Lithofacies (TC-FDL)

The Fissile Dark Lithofacies has a gradational relationship with the TC-SML and consists of black to sometimes purple or green, very well laminated, rippled, very fine quartz sandstone to siltstone with scattered dessication cracking. The *Skolithos* trace fossil was present but rare in some areas with those in the uppermost portion if the lithofacies being infilled with the above New Mountain Sandstone sediments. This indicates the *Skolithos* trace fossil inhabited up to the very late stages of the TCzst. Desiccation cracks were observed and often showed evidence of compression, forming a 'zig-zag' type structure.

The upper contact of the TC-FDL is very sharp and, in some places, clearly erosional. TC-FDL rip-up clasts were commonly observed overlying the NMSst at some locations.

5.3 Facies Distribution and Relationships in Observed Sections

The lithofacies described and their variations are represented in stratigraphic columns (Appendix A1) and discussed moving from north to south from the Taylor to the Wright Valley.

5.3a Nibelungen Valley

The bottom contact of the TCzst is gradational with the underlying WG-GCL. This was identified from other localities as the TCzst is generally in gradational contact with the underlying much finer grained Cross Bedded Sandstone Lithofacies of the Windy Gully Sandstone.

The TCzst at this location measures approximately 4m thick with the basal 1m, the TC-SML, being very well laminated, fissile and interbedded with green/khaki and mottled grey/tan layers. These layers were of slightly coarser content and contained fine quartz sandstone with rare scattered quartz granules. The remaining 3m of TCzst, the TC-FDL, consists of the black, very well laminated, fissile very fine sand to siltstone. The upper limit of the TC-FDL contains desiccation cracking indicating subaerial exposure. *Skolithos* trace fossils were observed and infilled with fine to medium quartz New Mountain Sandstone in the upper limits. The upper contact of the TC-FDL was very sharp but was not erosional at this location although the infilled trace fossils imply a hiatus.

5.3b Knobhead (Handsley Valley)

The TC-SML spanned almost the entire thickness of the TCzst section in this area with the TC-FDL appearing in the latter 2m of the section. The TC-SML measured approximately 38m thick and was consistently pale to mottled green with horizons of syneresis cracks observed at 19m (approx in middle of section, see photo 3.3-1). Syneresis cracks are also observed in the TC-FDL in the uppermost reaches of the unit also, (see photo 3.3-1).

The Knobhead section of the TCzst is quite different from its equivalents elsewhere due to the extensive thickness of the Sandy Mottled Lithofacies (TC-SML) and a very thin upper Fissile Dark Lithofacies (TC-FDL) (see figure 5.1 & appendix A1).

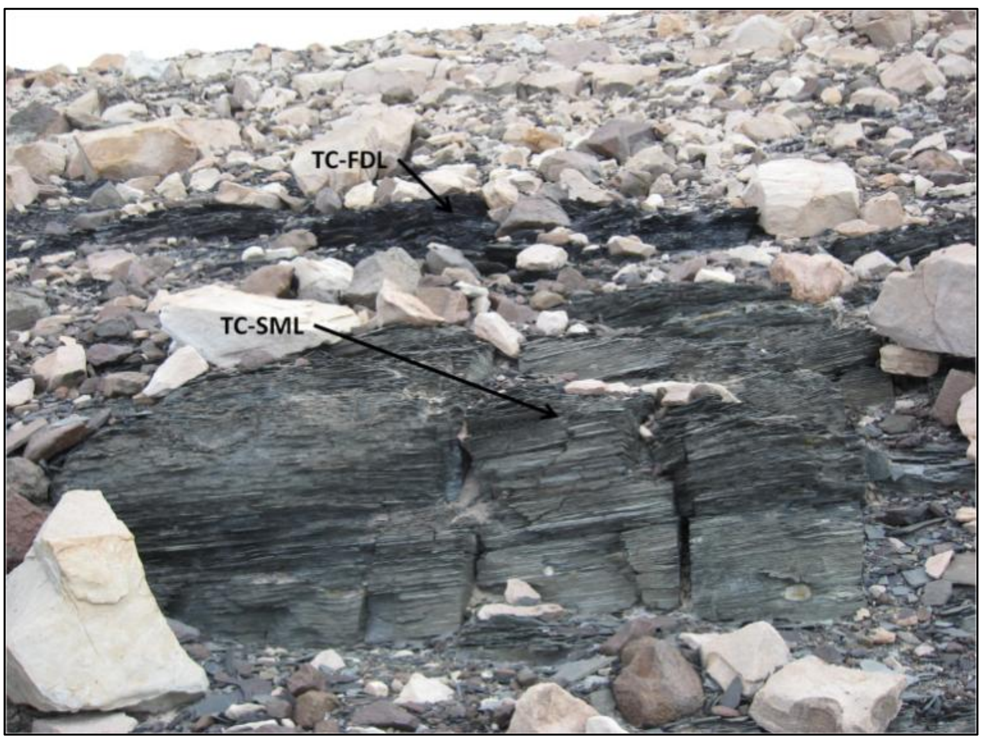

Figure 5.1 The TCzst gradational contact from TC-SML to TC-FDL, Knobhead

A majority of the TC-SML attributes in this section are typical, such as, being very well laminated, fissile and having preserved desiccation cracks. However it also contains scattered horizons of fine grained quartz sandstone cross beds approximately 0.5m thick (see figure 5.2), concretions and speckling (most likely secondary). The cross bedded sandstones indicate an influx of sand sediment possibly from a tidal event.

Figure 5.2 Cross bedded quartz sandstone within the Terra Cotta Fissile Dark Lithofacies, Knobhead (Handsley Valley)

A vey coarse pebble to cobble horizon was also observed towards the top the TC-FDL and contained very fine quartz sandstone that are flat and lensoidal in shape. The TCzst again has very sharp erosional contact with the overlying New Mountain Sandstone (further explained in chapter 6) .

5.3c New Mountain (Windy Gully)

The Terra Cotta Siltstone Formation (TCzst) in the New Mountain field site (Windy Gully) was seen in two sections separated by the extensive dolerite sills. Below the sill the TCzst measures 5.5m. Above the dolerite sill is a further 19m of TCzst, 14m of which have been identified as TC-SML and the upper 5m being TC-FDL. Although affected by the dolerite sill an estimate of the TCzst lithofacies can be estimated to; TC-SML = 19.5m and TC-FDL= 5.5m.

The TCzst below the sill is composed of TC-SML consisting of slightly fissile brown to green, well laminated, very fine sandstone to coarse siltstone units. Starved rippled assemblages were seen deposited in scoured channels (see figure 5.3). Also seen sporadically throughout the lower TCzst are syneresis crack assemblages (see figure 5.4).

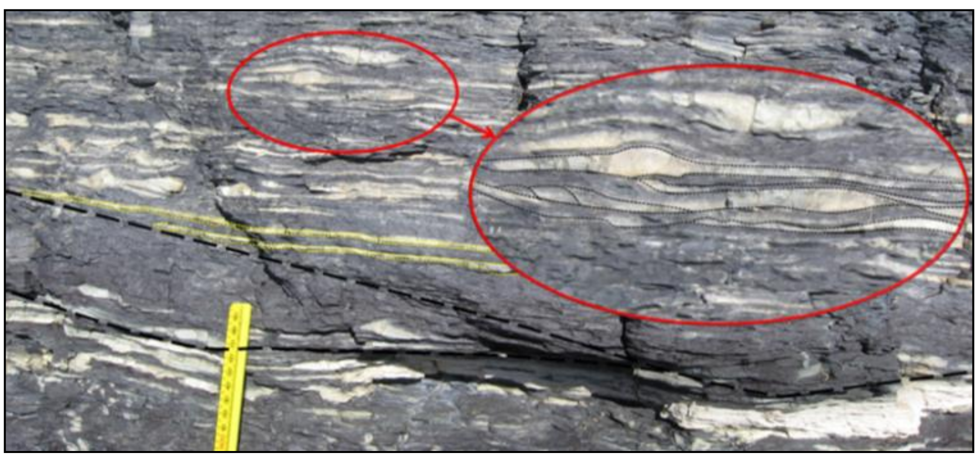

Figure 5.3 Sandy Mottled Lithofacies of the Terra Cotta Siltstone (TC-SML) showing parallel laminations at the base (yellow) and starved ripples with some scouring (small dashed black) and simple burrows (*Skolithos*?) toward the top of the image, New Mountain, Windy Gully. Note: red oval showing enlarged portion on right

Above the dolerite sill, the TCzst is TC-SML consisting predominantly of interbedded fissile mottled brown to purple black, well laminated very fine sandstone to siltstone and creamy white very fine quartz sandstone. The finer dark units often contain asymmetrical ripples with paleocurrent directions trending in a NE direction.

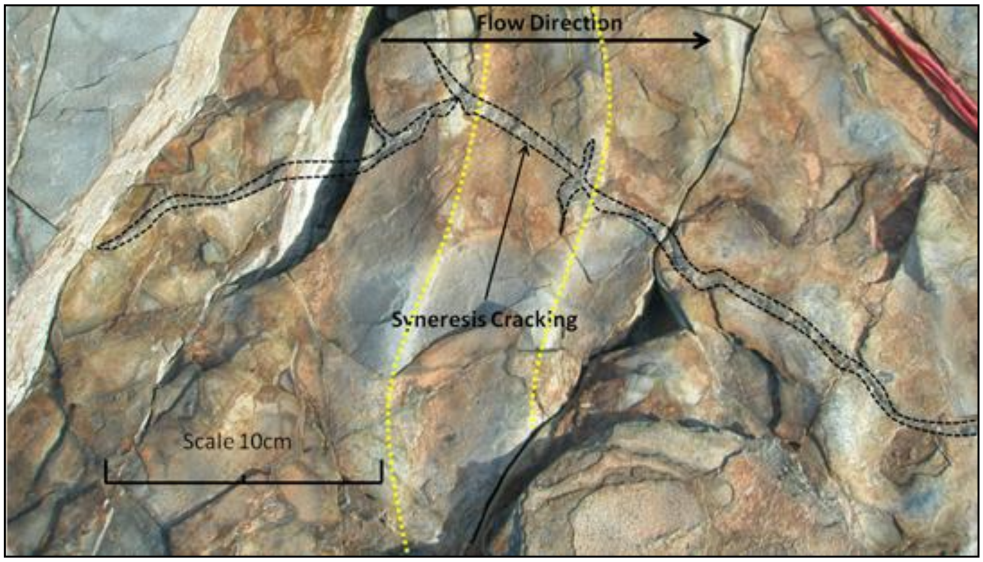

Figure 5.4 Asymmetric ripples (Crests along yellow dashed line) with syneresis cracks (black dashing) trending NE in the TC-SML, New Mountain, Windy Gully

The upper 5m of the TCzst has been identified as TC-FDL and consists of very well laminated black fissile siltstone. The TC-FDL also has no mottling discoloration and no quartz sandstone influx seen in the lower measures. Also seen in the TC-FDL are trace fossil assemblages of *Heimdallia* (see figure 5.5)

Figure 5.5 Trace fossil *Heimdallia* in the TC-FDL, Knobhead (Handsley Valley)

The upper contact of the Terra Cotta Siltstone Formation with the New Mountain Sandstone show desiccation cracking and therefore indicates subaerial exposure. This is consistent with eroded sites in the north but with a lack of erosion. It is suggested that at this location the Terra Cotta Siltstone Formation was exposed and subsequently dried before the influx of New Mountain Formation beach sediments initiated

5.3d Rotunda

The TCzst was seen at the Rotunda field site with direct contact with a large dolerite sill along its base. The TC-SML measures ~14m and consists of well laminated reddish-brown very fine sandstones with asymmetric and starved ripples. The red very fine sandstones are interbedded wit much paler sandstones of similar grain size. This is replaced with ~6m of the TC-FDL.

This shows predominantly fissile and very well laminated very fine sandstones to siltstones and has no observed ripple assemblages. The upper contact with the New Mountain Sandstone Formation show compressed desiccation cracking suggesting subaerial exposure after deposition.

5.4 Discussion and Interpretation of Depositional settings

The Terra Cotta Siltstone (TCzst) (with its characteristic purple-brown to mottled green coloration and rippled very fine sand to silt structure) acted as a clear horizon to differentiate the NMSst and WGSst above and below respectively. The TCzst varies greatly in thickness from a few meters up to 38m at Knobhead (Handsley Valley) and tends to thicken moving south. In the north however the WGSst has interbedded silt and sandstone lithofacies that may explain the unit thickness variations in the north.

The Terra Cotta Siltstone Formation in all observed areas includes both upper and lower lithofacies; the TC-SML and TC-FDL. Both Terra Cotta lithofacies range in thickness and as a whole are thickest at Knobhead (Handsley Valley). Progressing south the thicknesses of the TCzst are shown in figure 5.6.

	Thickness (m)		
Location	TC-SML	TC-FDL	Total
Nibelungen Valley	1	3	**4**
Knobhead (Handsley Valley)	38	2	**40**
New Mountain (Windy Gully)	19.5	5	**24.5**
Rotunda	14	6	**20**

Figure 5.6 Terra Cotta Siltstone Formation thicknesses observed in the field areas moving progressively south

In the two more southern sites the TC-SML is much thicker with relatively thin TC-FDL in the upper measures. The Nibelungen Valley however has the WG-ICSL (Windy Gully Interbedded Siltstone and Cross Bedded Sandstone Lithofacies), an interbedded succession of crossbedded quartzose sandstones and mottled very fine sandstones to siltstones. The presence of the Windy Gully Erosion Surface (bounding the top of the TCzst) indicates the true thickness of the TC-FDL may be thicker but not all areas along this horizon are erosional and therefore the thickness is still a good estimate. Terra Cotta rip-up clasts in the lower New Mountain Formation indicate an erosional relationship while desiccation cracking on the upper bound surface in the New Mountain location indicates sub aerial exposure and subsequent drying of sediments before the initiation of New Mountain Formation sediments.

The Terra Cotta Siltstone Formation throughout the field area represents two different environments; a prolonged tidally effected sandy estuarine environment (TC-SML) and a later very low energy salt marsh environment (TC-FDL).

Asymmetrical and starved ripples are seen in the TC-SML indicating sustained directional flow. Desiccation cracks indicate subaerial exposure of the Terra Cotta Siltstones and syneresis cracks indicate changes in salinity possibly from marine and fresh water influx.

The author suggests that the interbedded nature of the TC-SML indicates a tidally affected sandy estuarine environment with constant influxes of coarser fresh quartz sands. The existence of desiccation cracks indicate drying of sediments due to subaerial exposure, and syneresis cracking indicates salinity change, common in estuarine environment.

The Author suggests that the TCzst as a whole unit represents sand dominated, tidally effected estuarine environment moving to a lower energy and less tidally affected salt marsh environment before being truncated by the Windy Gully Erosion Surface (see chapter 6).

5.5 Conclusions

The author supports Bradshaw (1981) in terms of a marine setting .The Terra Cotta Siltstone Formation (TCzst) in all locations observed has consisted of the lower Sandy Mottled Lithofacies (TC-SML) and the upper Fissile Dark Lithofacies (TC-FDL).

The TCzst represents a tidally effected sandy estuarine environment shallowing up to a much lower energy and less tidally effected salt marsh or mud flat environment. This has been identified by the two lithofacies (the TC-SML and TC-FDL). The TC-SML represents a tidally influenced sandy estuarine environment containing bioturbated fine sand quartz components with coarser grain influxes, whilst the TC-FDL represents a less marine influenced salt marsh or mud flat environment beyond marine influx capability.

Desiccation and, in places, syneresis cracking is seen throughout the TCzst indicate subaerial exposure, resultant wetting and drying, and salinity changes common in an estuarine environment.

6. Chapter 6 - The Windy Gully Erosion Surface

6.1 Introduction

The Windy Gully Erosion Surface represents the very sharp, and in places erosional, contact between the Terra Cotta Siltstone and New Mountain Sandstone Formation. The top contact of the TCzst has been previously disputed and named the Windy Gully Erosion Surface (Harrington, 1965) and is observed as being erosive in places. The Windy Gully Erosion Surface was later discounted as not being regionally important (McKelvey, 1972).

6.2 Erosion Surface Variation by Location

The Windy Gully Erosion Surface was only seen at one location, in the Handsley Valley. Elsewhere in the field the contact between the Terra Cotta Siltstone and the New Mountain Sandstone is very sharp, indicating a sustained break in sedimentation. However, in the Handsley Valley the contact between the Terra Cotta Siltstone and the above New Mountain Sandstone Formation is seen as erosional due to the presence of Terra Cotta rip-up clasts.

This indicates a drop in base level but not to the same degree to what is seen on other erosion surfaces seen elsewhere in the field. Desiccation cracking elsewhere on the upper Terra Cotta Sandstone Formation horizon suggests subaerial exposure also indicating a sea level fall

6.3 Discussion and Interpretation of Depositional Settings

The Windy Gully Erosion surface has been disputed due to the lack of lateral extent. The presence of Teaar Cotta rip-up clasts in the directly overlying NM-BCL and the presence of desiccation cracks elsewhere indicates a drop in base level suggesting erosion and subaerial exposure respectively. The Windy Gully Erosion Surface, being only represented locally still indicates a sustained drop in sea level.

6.4 Conclusions

The Windy Gully Erosion Surface represents an isolated erosional period resulting in the deposition of Terra Cotta rip-up clasts. These clasts were deposited as the New Mountain Basal Conglomerate Lithofacies as a result. The degree of erosion has been identified to be to a lesser degree than other erosion surfaces seen elsewhere indicating only a small base level drop

In many of the locations in the field the Terra Cotta Siltstone Formation has a very sharp upper contact but the presence of Terra Cotta rip up clasts (in the Basal Conglomerate Lithofacies of the New Mountain Sandstone Formation) and desiccation cracks on the upper bounding surface indicate erosion and subaerial exposure respectively.

7. Chapter 7 - New Mountain Sandstone Formation

7.1 Introduction

The New Mountain Sandstone Formation (NMSst) is in the Taylor group is bound between the underlying Terra Cotta Siltstone Formation (TCzst) and the overlying Odin Arkose Member of the Altar Mountain Formation. The NMSst is bound between two erosional contacts; the upper being the Heimdall Erosion Surface (HES) and the lower being the debated Windy Gully Erosion Surface. At all sites observed in the Taylor and Wright Valleys the Sandstone Formation was deposited on the Terra Cotta Siltstone Formation and in no instances directly on the underlying Windy Gully Sandstone Formation or basement erosional surface (Kukri Erosion Surface - KES). The thickness of the New Mountain Sandstone Formation ranges between 70-145m

The New Mountain Sandstone Formation was seen throughout the field area and was one of the main formations of focus due to its association with the HES. It contains predominantly quartzose cross bedded sandstone successions with abundant trace fossil assemblages throughout. The NMSst is very similar lithologically to the Windy Gully Sandstone (WGSst) but is less feldspathic other than at its base. The New Mountain Sandstone Formation has been divided into lithofacies that become useful to show depositional patterns.

7.2 Lithofacies

The lithofacies of the New Mountain Sandstone Formation (NMSst) are described stratagraphically from the base moving upward. The lithofacies in the NMSst are based on sedimentary structures, presence of feldspar and trace fossils. The author assumes Walther's Law; that in an unbroken succession the depositional environments of the adjacent lithofacies, both vertically and horizontally must be compatible. This will later be compared with sequence stratigraphy to show the progression of depositional and environmental conditions. Lithofacies in this chapter will coincide as much as possible with Gilmer (2007) for comparison and consistency.

7.2a New Mountain Basal Conglomerate Lithofacies (NM-BCL)

The New Mountain Basal Conglomerate Lithofacies is bound at its base by the Windy Gully Erosion Surface. It contains sporadic assemblages of Terra Cotta Siltstone Formation rip-up clasts. The rip up clasts range in size from 2cm and up to 15cm in rare cases and all are comprised of green to brown, very fine sandstone to siltstone typical of the Terra Cotta Siltstone Formation. Where the rip-up clasts are not present this lithofacies is regarded as absent. The NM-BCL was only seen in the Knobhead (Handsley Valley) location and was measured up to 1m thick. The NM-BCL also consisted of coarse to medium, moderately sorted, cross bedded feldspathic quartz sandstones.

7.2b New Mountain Granule Cross Bedded Sandstone Lithofacies (NM-GCL)

The Granule Cross Bedded Sandstone Lithofacies is bound at its base either by the NM-BCL or the TC-FDL with either a sharp concordant contact or the Windy Gully Erosion Surface. It consists of moderately sorted, low angle, tabular to trough cross bedded, medium to coarse subfeldsarenite sandstone and is very similar to the NM-BCL minus the TCzst rip-up clasts. Granules of angular feldspar crystals and scattered pebbles of sub to well rounded quartz grains in this lithofacies (most commonly feldspar crystal granules) were confined to and concentrated in the foresets.

The cross beds were commonly 0.5-1.0 m thick and did not commonly contain trace fossils. This lithofacies is at its thickest in the Nibelungen Valley measured at 16 m.

7.2c New Mountain Low Angle Tabular Cross Bedded Sandstone Lithofacies (NM-Tabular CSL)

The Low Angle Tabular Cross Bedded Sandstone Lithofacies consist of low angle tabular cross bedded quartz arenites and sub feldsarenites (restricted to the lower NM-Tabular CSL). This lithofacies occurs both at the base and the top of the New Mountain Sandstone Formation with the NM-Tabular CSL in the middle. The cross beds are commonly 1-2m thick. The lithofacies above and below the NM-Trough CSL will be referred to as upper and lower NM-Tabular CSL respectively

Heimdallia trace fossil predominantly occurs in the lower lithofacies at the base of the New Mountain Sandstone Formation, whilst the *Skolithos* and sometimes *Diplicnites* trace fossil occurs in the upper lithofacies at the top of the New Mountain Sandstone Formation. The trace fossil *Heimdallia* varies in thickness from 10cm-2.0m and sometimes penetrates into lower successions. The horizons often form an entirely bioturbated massive horizon, sometimes occurs as an increasing amount of bioturbation progressing through the cross beds, or in rare cases exist as single traces.

Both symmetric and asymmetric ripples occur in the upper NM-Tabular CSL and coexist with scattered *Diplicnites* trackways. The ripples are observed on cross bed foresets and vary greatly in size and form from symmetric to very asymmetric.

Slumping is observed in upper limits of the New Mountain Sandstone Formation in the upper NM-Tabular CSL and is often associated with the overlying erosional surface, the HES. The convoluted beds range from whole cross bed sets to single foresets. The slumping horizons form coherent isoclinal folds and project laterally up to and over 200m in locations (such as the Nibelungen Valley).

The upper NM-Tabular CSL also has horizons of green, fine to very fine, sandstones and sometimes contains flame structures. The fine sandstones resemble Terra Cotta like sediments.

7.2c New Mountain High Angle Trough Cross Bedded Sandstone Lithofacies (NM-Trough CSL)

The High Angle Trough Cross Bedded Sandstone Lithofacies consist of high angle trough cross bedded quartz arenites. The lithofacies is confined between the upper and lower NM-Low Angle CSL with cross bed thickness ranging between 1-2m. Trace fossils throughout the lithofacies are scattered and predominantly consist of *Heimdallia* bioturbation

7.3 Overview

The sedimentary sequence of the New Mountain Sandstone Formation from bottom to top where it overlies the Terra Cotta Siltstone Formation begins with a Basal Conglomerate Lithofacies (NM-BCL) that consists of Terra Cotta rip-up clasts of various sizes. This is followed by the Granule Cross Bedded Lithofacies, a medium to very coarse cross bedded feldsarenite with scattered pebble horizons. This is overlain by the lower Low Angle Tabular Bedded Sandstone Lithofacies, the middle High Angle Trough Cross Bedded Sandstone Lithofacies and the upper Low Angle Tabular Cross Bedded Sandstone Lithofacies. The three CSL lithofacies contain a variety of trace fossil assemblages and distinctive slumping horizons. The Cross Bedded Sandstone Lithofacies is the most abundant and comprises almost the entirety of the New Mountain Sandstone Formation. Fine green horizons are also observed in the uppermost NM-Low Angle CSL that resembles Terra Cotta sediments.

7.4 Facies Distribution and Relationships in Observed Sections

Specific localities are described below and stratigraphic columns are presented in Appendix A1 through stratigraphic columns. They will be discussed moving from north to south from the Taylor to Wright Valleys, Southern Victoria Land. The relationship with the basal Windy Gully Erosion Surface and the cross-cutting Heimdall Erosion Surface will be presented below where relevant but will be analyzed in more detail in the erosion surface sections.

7.4a Nibelungen Valley

The NMSst in the Nibelungen Valley is fully exposed from base to top, although obscured in places by rubble and snow (see stratigraphic column #1). The basal contact with the Terra Cotta Siltstone Formation is very sharp but with no evidence of rip-up clasts as seen elsewhere. Therefore the basal unit is the NM-GCL.

The NM-GCL is approximately 16m thick and consists of medium to coarse low angle tabular cross bedded sub feldsarenite sandstones. Angular granules are often concentrated along foresets within the medium to coarse sandstones with feldspar content ranging between 2-7%, decreasing upwards. *Heimdallia* trace fossils are seen in sporadic horizons approximately 1-2m thick creating massive beds in finer sequences within. The NM-GCL then becomes massive over 1m and is truncated by a succession of well sorted NM-CSL successions.

The upper NM-Tabular CSL, as mentioned, abruptly truncates the NM-GCL and consists of well sorted, fine to medium, trough cross bedded, quartzose sandstones. The total thickness of the upper and lower NM-Tabular CSL and the NM-Trough CSL measures at least 36m, but the section was unable to be completed due to accessibility issues. GPS recordings of the NMSst close by gave an estimate thickness of the unit to be 55m. At the base of the lower NM-Tabular CSL, a slumped horizon measured 0.7m was observed forming undulating beds from cross bedded units (see figure 7.1A). Directly above the slumped surface were scattered clasts of finely laminated sandstones of the same composition of the NM-CSL (see figure 7.1B).

Figure 7.1A Slumping horizon at the base of the NM-CSL below large trough cross bed

Figure 7.1B Rip-up clasts observed in the sediments directly above the slumping horizon in the lower NM-CSL, Nibelungen Valley

Immediately above the slumping horizon was an unusually large single trough channel structure measuring 33m wide and 2.4m high. The channel axis trend and plunge was measured at 279/12°W.

The remaining NM-Trough CSL consists of very well sorted, medium to low angle trough cross bedded sandstones with intermittent horizons of *Heimdallia* and *Skolithos* varying from 0.5-2.5m thick. The *Heimdallia* beds were recorded over the next 6m as massive, fully bioturbated horizons with very little to no remnant cross bedding preserved.

The uppermost 5m of the New Mountain Sandstone Formation consisted of the NM-Tabular CSL before the HES, became increasingly lower angle and coexisted with the introduction of abundant *Skolithos*. The HES truncated the NMSst in this area showing a saw tooth pattern along protruding cross bed foresets, similar to what is seen elsewhere in the field. The upper NM-Tabular CSL also contained intermittent *Diplicnites* track ways at its base. These were seen on cross bed foresets before becoming replaced with *Skolithos*. Note that the track ways were only observed where the cross bed foreset faces were exposed; unlike *Heimdallia* and *Skolithos, Diplicnites* do not burrow therefore are not easily seen in cross section.

Strike and dip measurements were taken from the Nibelungen cross bed foresets, ripples and trough axis to determine paleoflow directions. The paleoflow directions indicate an east to west trend with the greatest flow directions trending west and southwest.

7.4b Folkvanger Valley

Only the upper 5m of the upper NM-Tabular CSL was seen in the Folkvanger Valley due to extensive rubble throughout the lower areas and thus very poor exposure of anything below the HES. (see Strat Column; appendix A1).

The visible upper NM-Tabular CSL is extensively slumped and consists of very well sorted, fine to medium, quartz sandstone with coherent cross bed laminations. The slump horizon extends for over 10m laterally, until obscured by rubble, and is commonly thicker than 1m occasionally thickening to over 2m (see figure 7.2A&B). Slumping involves the entire cross bed set and shows highly ductile folding with coherent isoclinal folding to form convolute bedding. The slump beds occur within close proximity to the HES horizon but are not truncated in this case.

Figure 7.2A&B Slump horizons directly below the HES, Nibelungen Valley

Above and below the slumped horizon are 1-1.5m thick, low angle, tabular cross beds with sporadic and sparse horizons of *Skolithos* trace fossil. The exposure of these cross beds is poor so measurements were estimated.

7.4c Knobhead (Handsley Valley)

The NMSst at Knobhead (Handsley Valley) is well exposed throughout most of the succession with scattered sections of obscured stratigraphy. Due to the extent of the outcrop and time constraints, total thickness measurements were taken by handheld GPS. According to GPS readings in the New Mountain field area, the New Mountain Sandstone Formation had a maximum thickness of 144m in this location, but the intrusion of a single dolerite sill makes this an estimate.

The Basal Conglomerate Lithofacies (NM-BCL) is 1m thick and contains scattered quartz pebbles and rip-up clasts that appear to be Terra Cotta Siltstone Formation (see figure 7.3A&B). The rip-up clasts are likely to be the product of an erosional event between the deposition of the Terra Cotta Siltstone Formation and the initial New Mountain Sandstone Formation. Some sparse *Heimdallia* horizons are present but only where the grain size fines to medium sand.

Figure 7.3A&B Terra Cotta rip-up clast observed in New Mountain Basal Conglomerate Lithofacies (NM-BCL), Handsley Valley

Overlying the NM-BCL is ~2m of Granule Cross Bedded Sandstone Lithofacies (NM-GCL) laterally thickening to ~4m thick. The granules are composed of coarse sand-sized quartz and feldspar grains concentrated along low angle tabular cross bed foresets. The overlying cross-bedded sandstone lithofacies is 70m thick before being cut by a dolerite sill with another 70m present above it.

The bioturbated sediments were associated with lower angle tabular cross beds. The lower NM-Tabular CSL had *Heimdallia* bioturbation whilst the upper NM-Tabular CSL had *Skolithos*. At this location the *Skolithos* trace fossil was constrained to the upper limits of each cross bed succession. This suggests a period of quiescence or lack deposition enabling the *Skolithos* organism to form the burrowed structure. The NM-Trough CSL again had scattered *Heimdallia* and *Skolithos* trace fossil assemblages.

The upper contact of the NMSst in this location was difficult to locate as the HES was not erosional here. The upper contact was chosen to be where there is rapid introduction of feldspar coinciding with a coarsening in grain size and rapid disappearance of *Skolithos.* Grain size ranges from granule to pebble and cobble indicating the presence of the overlying Odin Arkose Member of the Altar Mountain Formation (Chapter 9).

Paleoflow measurements were not able to be taken due to constant poor weather and time constraints.

7.4d New Mountain (Windy Gully)

The total thickness of NMSst in the New Mountain (Windy Gully) Location is approximately 135m (see start column XXX). Neither the NM-BCL nor the NM-GCL is present at this location but is replaced by a feldspathic NM-Tabular CSL. The basal contact of the NMSst lies directly on desiccation cracked Terra Cotta Siltstone indicating a period of subaerial exposure before the New Mountain Sandstone Formation deposition (see figure 7.4).

Overlying the desiccation cracks is 18m of lower NM-Tabular CSL. This is well sorted, fine to medium, very low angle tabular subfeldsarenite. The low angled cross beds are a rust brown colour and are interbedded with very fine sandstone horizons with elongate asymmetrical ripples.

Figure 7.4 Desiccation cracking in the lower New Mountain Sandstone Formation Cross Bedded Sandstone Lithofacies, New Mountain, Windy Gully.

The author suggests that this section of the lithofacies indicates a lower energy environment in a relatively shallow water depth resulting in the fine sediment drapes and rippling.

Over the next ~20m the lower NM-Tabular CSL consists primarily of heavily bioturbated tabular cross bedded sandstones. A defining feature of this location was the degree of bioturbation by *Heimdallia*. *Heimdallia* beds measure ~1-3m thick of completely reworked medium quartz sandstones, but in some cases only partially reworked.

In places, the bioturbated cross beds were still preserved but became increasingly bioturbated from base to top. These beds repeated indicating a cyclic relationship

Approximately 40m of the NM-Trough CSL consisted of well sorted medium to fine quartz arenites and had scattered *Skolithos* trace fossils but were sparse. The trough cross bed thickness was commonly 0.5-1m.

The upper NM-Tabular CSL measured between 1-2m and commonly had ripples surfaces along cross bed foresets. A foreign trace fossil track way was observed close to the upper bounding surface of the NM-CSL. The track way extended over 1m along a rippled surface and contained digital markings either side of an axial trough (see figure 7.5). This trace fossil is similar to the *Diplicnites* but with an axial trough. The mode of transport appears similar to *Diplicnites* and over the rippled surface suggests the trackway was on consolidated sand.

Figure 7.5 Trace fossil track way along rippled surface in the New Mountain Sandstone Formation, New Mountain (Handsley Valley)

The NM-Tabular CSL formed thicker cross sets from 1-3m thick of much more tabular cross beds. The thicker cross beds were no steeper in foreset dip but were comprised of coarse quartzose sand. In addition, thin green very fine sand drapes were observed between the cross bed sets. Furthermore the unit was bound at its top by 20cm dark green very fine sand to mud unit with asymmetrical southern trending ripple horizons, very similar to the Terra Cotta Siltstone Formation.

The following 40m of the upper NM-Tabular CSL consisted of alternating beds of light green very fine quartz sandstone and well sorted cream medium much lower angle more tabular cross bedded sandstones (see figure 7.7). There is a notable lack in trace fossils. Ripples occur in the light green sandstones with paleoflow measured trending constantly south (see figure 7.6).

Figure 7.6 Asymmetric ripple assemblages in the New Mountain Sandstone Formation, New Mountain (Handsley Valley)

Figure 7.7 Tabular cross bedded sandstones of the uppermost New Mountain Sandstone Cross Bedded Sandstone Lithofacies, New Mountain (Windy Gully)

The final 6m of the upper NM-Tabular CSL shows a sudden grain size increase over a 0.5m interval from well sorted fine to medium (mostly fine) quartz sandstone to predominantly medium sand. The cross beds become very low angle and almost flat lying in places and coincide with the rapid introduction of the trace fossil *Skolithos*, leaving very little cross bed foreset fabric (see figure 7.8).

Figure 7.8 Transition from steeper trough to shallow tabular cross beds and the introduction of *Skolithos* in the uppermost NMSst New Mountain (Handsley Valley)

After the increase in grain size and introduction of *Skolithos*, the initial influx of arkosic sediments determines the Heimdall Erosion Surface (although here not erosional) thus marking the uppermost contact of the NMSst.

7.4e Rotunda

The Rotunda field site proved very difficult to measure and record as there was extensive snow coverage. The exposure of sections consisted of lengthy sweeping of outcrops before describing. Portions of the section were grouped and changes were recorded by height measured from handheld GPS.

Neither the NM-BCL nor the NM-GCL was seen at this location and the base of the NMSst was not located at this site due to accessibility problems. However, observed NM-CSL lithologies measured 78m thick providing a minimum total thickness.

At the base of the section contains approximately 50m of very large, 2-2.5m thick, low angle, cross stratified tabular cross beds of the lower NM-Tabular CSL with fine millimetre scale cross bed laminations. The cross bedded unit contains well sorted quartz arenites with scattered horizons of coarse sand and was capped at its top by a 2m thick very finely laminated and sometimes rippled green sandstone. Desiccation cracking is also observed at the base of the unit suggesting a wetting-drying scenario in the early stages of the New Mountain Sandstone Formation.

An increase of grain size to medium to coarse sandstone sought the initiation of the NM-Trough CSL. The coarser quartz grains were again concentrated to the cross bed foresets and towards the top of this lithofacies were altered by slump horizons up to ~2m thick.

The introduction of the upper NM-Tabular CSL coincided with the gradual reintroduction of the trace fossil *Skolithos*. *Skolithos* was introduced over 6m before becoming abundant for over 17m. The upper NM-Tabular CSL again consisted of well sorted fine to medium cross bedded quartz arenites but with no evidence of silt laminations before the initiation of feldspar.

The upper contact with the overlying Altar Mountain Granule Cross Bedded Sandstone Lithofacies (Odin Arkose Member) is conformable and identified by the abrupt introduction of 10-15% feldspar and a grain size increase. The grain size increase coincides with a sudden decrease of *Skolithos* abundance becoming very sparse. The grain size change was from well sorted medium quartz sandstone to moderately sorted very coarse sand to angular granule feldspar with coarse sub rounded to rounded subfeldsarenite. The author suggests that the New Mountain Sandstone Formation was not subject to an erosional environment but by an influx of feldspar rich sediments.

Paleoflow directions at Rotunda trended toward the northwest direction indicating a south to southeast direction.

7.5 Discussion and Interpretation of Depositional Settings

The New Mountain Sandstone Formation has previously had a variety of interpretations of depositional setting in a range of different localities throughout Southern Victoria Land, Antarctica. These include marine, fluvial (braided river) and sub aerial (aeolian) in origin (Barrett and Kohn, 1975; Barret, 1977; Bradshaw, 1981; Plume, 1982; Woolfe, 1990; Wizevich, 1997). The author presents his interpretations for the southern Dry Valleys region based on detailed stratigraphic and sedimentologic description at 5 localities.

The New Mountain Sandstone Formation was present throughout the entire field but varied in lithofacies thickness (see figure 7.9). The total thickness of the NMSst was at its thinnest in the northern most sites (17m), for example the Nibelungen Valley, and thickened in the southern sites (144m), for example Knobhead. This is however difficult to fully determine as the site furthest south (Rotunda) was not fully exposed therefore a minimum thickness can only be recorded. The author speculates that as the bottom most observations recorded low angle tabular cross beds, this indicates that the point was relatively low in the succession therefore making the NM-CSL thickness close to what was recorded. Throughout the field the New Mountain lithofacies varied in thickness also moving southward and in a number of locations nonexistent (see figure 7.9), this is seen particularly in the NM-BCL.

	Lithofacies Thickness (m)			
Location	NM-BCL	NM-GCL	NM-CSL	**Total**
Nibelungen Valley	Vacant	16	55	**71**
Folkvanger Valley	Not seen	Not seen	>5m	**NA**
Knobhead (Handsley Valley)	1	2	141	**144**
New Mountain (Windy Gully)	Vacant	Vacant	135	**135**
Rotunda	Not seen	Not seen	78	**>78**

Figure 7.9 Summary of NMSst lithofacies thicknesses throughout the field, moving from north to south

The composition of the New Mountain Sandstone Formation is dominated by quartz, is lacking lithics and has feldspar in the lower part of the formation. The base of the NMSst consists of two main lithofacies; the NM-GCL and the NM-BCL (the NM-BCL being of the same composition but with Terra Cotta type rip-up clasts). Both the NM-BCL and the NM-GCL contain moderate to poorly sorted, cross bedded, medium sand to granule feldspathic quartz sandstone. This lithofacies is comparable to Gilmer (2008) as it contains rip-up clasts but in this case they are composed of clasts that appear to be Terra Cotta Siltstone Formation. In addition the matrix that supports the clasts include granular quartz and feldspar instead of pebble clasts. The author suggests that in the field area the NM-BCL and NM-GCL is the result of a rejuvenation scenario where the feldspathic sediments were still present due to insufficient weathering. Furthermore, the range and grain size of the NM-BCL and NM-GCL suggests that the depositional environment was further from source than what was seen in Gilmer's (2008) locations as her Basal Conglomerate Lithofacies contains larger grains and a range of lithics. .

The cross bedded portion of the New Mountain Formation has been divided into lower NM-Tabular CSL, NM-Trough CSL and upper NM-Tabular CSL. The Cross Bedded Sandstone Lithofacies consists of essentially cross bedded medium to fine quartz arenites with differing cross bed forms and trace fossil association. The lower NM-Tabular CSL consists of low angle tabular cross beds with differing *Heimdallia* trace fossil interactions. The *Heimdallia* trace fossil ranged from destroying any fabric, to partially reworking the cross bed sets; where cross bed fabric was partially preserved and the bioturbation was throughout but greatest at the top of the cross bed set. The existence of *Heimdallia* throughout cross bed sets where the degree of bioturbation is greatest at the top indicates that the cross bed successions were deposited with active bioturbation throughout deposition and also before the next cross bed set was initiated. The presence of feldspar in this lithofacies indicates an earlier stage of reworking of feldspathic sediments. The feldspathic sediments have therefore been progressively reworked and eroded out in the following lithofacies. The lower NM-Tabular CSL therefore suggests a low angle beach environment with marginal interaction with a Terra Cotta setting in places where it is draped in dark green very fine sandstones.

The NM-Trough CSL contains successions of well sorted medium to fine trough cross bedded quartz arenites. The cross bedded sandstones contained sparse *Heimdallia* and *Skolithos* trace fossil horizons but in a majority of the section these were absent. The cross beds were steep angle and of trough structure, and in places consist of large isolated trough structures. The NM-Trough CSL has some slump horizons but they are mainly confined to the upper NM-Tabular CSL. The slump horizons show laterally extensive convolute bedding with coherent laminations indicating high ductility during formation. The trough cross bedding suggests an increase in water depth and therefore a progression into a shallow marine setting rather than beach sediments. The slumping horizons however indicate a storm event resulting in the inconsolodation of sediments.

The upper NM-Tabular CSL is physically similar by comparison to the lower NM-Tabular CSL and consists of low angle tabular cross beds but lacks feldspathic content and contains abundant *Skolithos* rather than *Heimdallia* trace fossils. The author suggests that the appearance of *Skolithos* and the grain size change is a significant proxy for the trace fossil's environmental conditions. The upper bound contact of the NM-CSL, the HES, varies from erosional in the northern sites and relatively conformable in the south. The author suggests that the NM-Tabular CSL represents a transition back to low angled beach deposits and in places interacting with a Terra Cotta type environment due to the green very fine sand drapes and ripple assemblages. The extensive slump horizons in the uppermost NM-Trough CSL suggest inconsolodation most likely from storm events.

The Cross Bedded Sandstone Lithofacies show physical similarities to the deposition of channel trough cross beds followed by transverse bar tabular cross stratification but lacks key features such as scour surfaces, conglomerate (coarse grain) lags and mud drapes. Sandy braided rivers are gradational in profile and the formation and migration of transverse bars produce both tabular and trough cross beds with reactivation surfaces with gravel lags at the base and mud drapes at the top. Coleman (1969) studies the Brahmaputra River, India and describes the river sediments consisting of trough cross bedded fine sands with clayey silts. This however is ruled out as the continually cross bedded sandstones of the New Mountain Sandstone only show very fine sand drapes in the low angle tabular cross bed sets and is often paired with ripple assemblages indicating a shallow water depth. Gravel lags are also absent in both the tabular and trough cross beds. The author also suggests that it would be more likely to see cyclic successions of fluvial environment deposition through channel migration but what is seen in the field is one single succession.

The Basal Conglomerate (NM-BCL) and Granule Cross Bedded Lithofacies (NM-GCL) in the New Mountain Sandstone Formation shows characteristics of a gravelly braided river but consists predominantly of tabular and consistent grain size cross bed sets. This again does not contain sufficient grading and presence of gravel lags or mud drapes. This therefore suggests a granular beach setting with the influx of feldspathic sediments.

Overall, the New Mountain Sandstone Formation is very consistent and has very little variation in grain size and sedimentary structures. It is therefore concluded that the NM-CSL is not of fluvial origin.

Aeolian environments are characterized by large scale cross bedding, pin striping, ‘frosted’ grain surfaces, high index ripples, and lack of mica and clay minerals (Collinson, 1986a; Mazzullo *et al*, 1991; Trevena and Cole, 1999;

Loope, 2004). The physical characteristics of aeolian deposits can be very similar to shallow marine deposits except for the frosted grains (Gilmer, 2008).

One defining feature of the New Mountain Sandstone Formation in the field sites was the presence of slumping at intermittent periods. The slumping feature was determined to be a significant geological feature in the New Mountain Sandstone Formation as it represents inconsolodation of the New Mountain sediments suggesting storm events. Analysis of the NMSst shows that the slumping horizons occur in well sorted, cross bedded quartzose sandstones. The slump horizons are predominantly coherent isoclinal folds and are often very tightly bound, showing a very ductile deformation scenario. The slump horizons occur throughout the NMSst both over whole cross bed successions and also along single or grouped cross bed foresets.

The Heimdall Erosion Surface truncates the convolute bedding in the Northern field sites (Nibelungen and Folkvanger valleys) in particular but in some other locations is incorporated into the slump horizons also. The author suggests that periodic storm events in a marine environment are a probable cause for the disturbance of the low angled cross bedded sandstones. Theories including the flooding of dune environments (Weizevich, 1996) are challenged due to the ductility of such horizons.

Paleoflow directions for the New Mountain Sandstone Formation do change from north to south in the field area. In the northern sites, such as the Nibelungen and Folkvanger Valleys, the paleoflows trend towards west to southwest whilst the southern sites, such as New Mountain (Windy Gully) and Rotunda, trend towards north to northwest. Rippled horizons in the NMSst varied greatly from symmetrical to asymmetrical (elongate and domed to pointed in cross section). These asymmetrical ripple assemblages were commonly transverse sinuous and in and out of phase and showed flow directions predominantly in a west direction.

The trace fossil *Skolithos* in the NMSst is believed to have occurred in a beach setting creating a partially cemented vertical channel very similar to what is seen on sandy beaches nowadays. The *Skolithos* trace fossil created a pitted surface and in some cases a raised crater type structure was preserved. The *Skolithos* trace fossil appears to be grain size dependent as it often appears suddenly when the grain size trends towards well sorted medium sand. This may be due to the ability to cement a particular grain size for the vertical tube structures.

The trace fossil *Heimdallia* is believed to be present shallow beach sediments as it was present throughout the lower NM-Tabular CSL. It was present in a greater range of grain size between very fine to medium sandstones and therefore less grain size reliant. This indicates that *Heimdallia* was present in lower energy and possibly greater depth water columns and finer grained environments.

Diplicnites is also believed to occur predominantly in a beach or very shallow water depth as it was seen on intermittent horizons in the upper and lower NM-Tabular CSL forming elongate and sinuous trackways. The author suggests that the trackways would only be preserved on consolidated sediments.

7.6 Conclusions.

The New Mountain Sandstone Formation (NMSst) moves from low angled tabular to higher angled trough and back to low angled tabular cross beds with variations in grain size and interaction of trace fossils. Differences between the NMSst and the WGSst include the confinement of feldspar to the basal cross bedded units and lack of feldspar thereafter.

The author supports Bradshaw (1981) suggesting similar environmental conditions to the Windy Gully Sandstone with tidally effected sand flats laced with channels but expands this to incorporate a transition between shoreline beach berm and shallow marine environments. In the upper and lower NM-Tabular CSL the presence of ripples and very fine sand draping suggest a shallow water column and interaction with a Terra Cotta type environment.

The shoreline deposits are represented by the low angle tabular cross bedded successions forming a low angle beach environment seen in the upper and lower NMSst sediments. In addition, the presence of feldspar at the base of the NMSst is suggested to be due to rejuvenation of the source sediments therefore initial presence is expected and subsequent reworking throughout the NMSst has removed the feldspar through weathering. The feldspar would have weathered to clay minerals and therefore washed out and transported elsewhere.

The steepening of cross beds and concave-up trough cross beds indicate a shallow marine transition and deepening of the water column forming a channelized environment.

Slumping in the New Mountain Sandstone Formation suggests the inconsolodation of sediments by either a storm event or a sudden increase in water depth.

8. Chapter 8 - The Heimdall Erosion Surface

8.1 Introduction

The Heimdall Erosion Surface (HES) is a disconformity that separates the quartzose New Mountain Sandstone Formation from the overlying subfeldsarkose to arkosic Altar Mountain Formation. The HES is confined to southern Victoria Land and changes laterally from a sharp erosive contact in the north to a conformable contact in the south (McKelvey *et al.* 1970, 1977). In the north the HES truncates the upper quartzose New Mountain Sandstone Formation and is overlain by the Odin Arkose Member of the Altar Mountain Formation. Moving south, the HES becomes more conformable where continuous sedimentation occurs between the New Mountain Sandstone Formation and the overlying Altar Mountain Formation the contact is identified as an influx of feldspar into the quartzose sandstones (McKelvey *et al.* 1977, Plume, 1978)

The Odin Arkose Member of the Altar Mountain Formation is comprised of a basal conglomerate directly above the HES. In this and later chapters it will vary in nomenclature to comply with other lithofacies described in the field. The Odin Arkose Member will therefore be referred to as the Altar Mountain Basal Conglomerate. This represents the lowest portion of the Altar Mountain Formation with characteristics and environmental conditions similar to basal conglomerates seen elsewhere in the field.

8.2 Erosion Surface Variation by Location

The HES is described by location moving progressively south from Mt Boreas to Rotunda in the Taylor and Wright Valleys. The HES is the erosional horizon, however features in the under and overlying sediments will be described and discussed to provide insight into the HES setting. Reasons for this include a direct relationship between HES characteristics and the Altar Mountain Basal Conglomerate Lithofacies (AM-BCL).

The Heimdall Erosion Surface varies in its characteristics from a sharp erosive contact with up to 0.5m relief to a relatively conformable introduction of feldspar and coarser grained quartzose sediments. The erosive HES horizons truncate low angle quartzose cross beds of the New Mountain Sandstone Formation resulting in characteristic saw tooth type surface, a remnant of the cross bed structures. This saw tooth pattern however is not as aggressive as what was seen in more northern sites (Gilmer, 2007) and form a more subtle pattern with the characteristic AM-BCL directly on top (see figure 8.2). The dip of the HES is difficult to determine but appears to be very low angle in the sites visited throughout the field season. The truncated cross bedded New Mountain Sandstone appears unweathered suggesting a relatively intense erosive period or being swept clean with little weathering profile. Small biscuit shaped sandstone clasts appear to be remnant cross bed foreset limbs and show a degree of discoloration possibly due to sustained weathering.

The HES surface appears to be syndepositional at one location with convolute bedding horizons within the New Mountain Formation but in most places is observed to be within close proximity to the convolute bedding or truncating them. The following sections describe the HES seen at 5 localities from the northern sites progressively moving south.

8.2a Mt Boreas

Exposure at Mt Boreas was poor due to extensive snow cover as the HES outcrop formed a bench. The HES was a sharp erosional contact with approximately 50cm relief (appendix A1). The overlying Altar Mountain Basal Conglomerate Lithofacies measures 20-30cm thick and consists of very poorly sorted, very coarse feldsarenite matrix supporting sub-rounded to well rounded quartz and sub-angular to angular feldspar pebbles, therefore forming a conglomerate. The conglomerate clasts are pebble to cobble in size, pink biscuits in shape, and are composed of well sorted, fine to medium, quartz sandstone of a similar composition to the underlying New Mountain Sandstone Formation (see figure 8.1). The pink discoloration suggests prolonged weathering of the clasts, however the New Mountain Sandstone directly below the HES was not discolored.

Figure 8.1 Close up of the Odin Arkose Basal Conglomerate Lithofacies on the Heimdall Erosion Surface containing pink sandstone biscuit shaped clasts both intact and fragmented, Mt Boreas

The HES shows a saw-tooth type pattern in profile due to irregular truncation across the cross bedded New Mountain Sandstone Formation (see figure 8.2). The saw-tooth feature of the HES commonly has a relief of 10-20cm up to as much as 50cm in places.

Figure 8.2 Subtle Saw-tooth pattern of the Heimdall Erosion Surface truncating the cross bedded New Mountain Sandstone Formation at the Mt Boreas site

The units observed in the Mt Boreas area had a spotty appearance, most likely as a result of the local Mata Intrusives causing early stage and low level metamorphism.

8.2b Nibelungen Valley

The HES at this site varies from relatively planar to irregular depending on the association with below NMSst. The HES has less than 10cm relief .

The saw-tooth irregular profile is still present in places but is also replaced by spectacular slump horizons (large and small scale). This was seen particularly on the east side of Plane Table (Figure 8.4A&B). The slumped horizons have been included in this section as the HES both truncates or is incorporated into the slumps.

The slump structures occur along broad surfaces of cross beds and within cross bed foresets, both showing ductile deformation. This was seen by coherent isoclinal folds and in some cases a more slurried or convolute bedding texture. Within the isoclinal folds are scattered HES conglomerate quartz clasts suggesting a period of ductile deformation either syndepositional with the HES event or soon after deposition (see figure 8.3). The slump horizons, especially at Plane Table, projected for over 200m laterally and were up to 1m thick in places (see figure 8.4). Furthermore, the slumping horizons occur both through whole cross bed sequences and single foreset limbs.

Figure 8.3 Basal conglomerate pebbles incorporated into the slump horizons directly below the HES

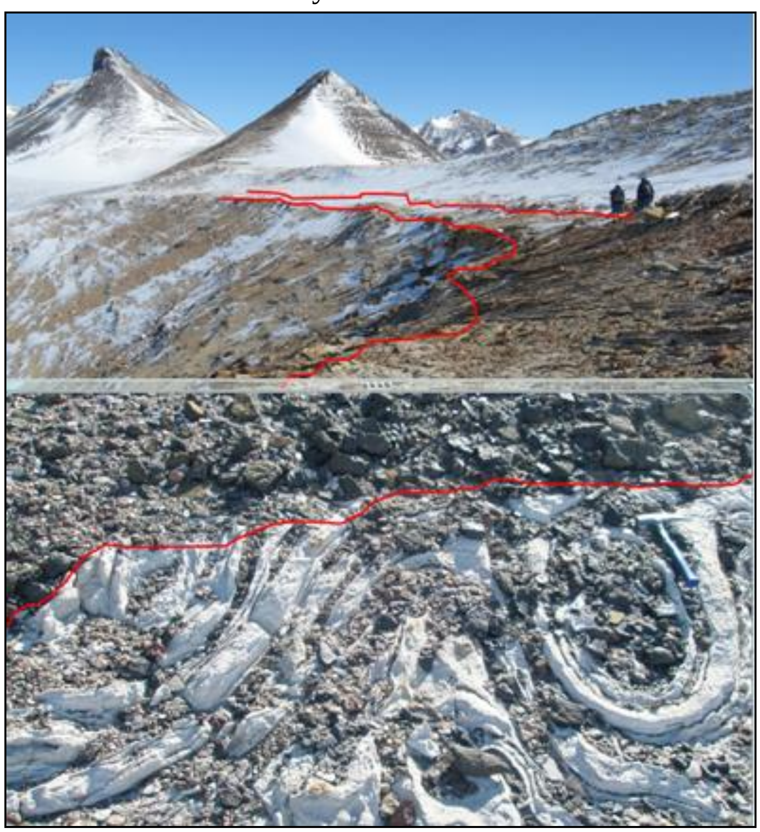

Figure 8.4 A&B Looking south, the HES truncating slumped beds (red line shows HES horizon plane) at Plane Table, Nibelungen Valley

Angular biscuit-shaped sandstone clasts are scattered directly on the HES and are relatively rare overall becoming locally abundant towards the west of base camp. The sandstone clasts range in appearance from well rounded 2-15cm flat biscuits to angular elongate slabs up to1m long (see figure 8.5). The author suggests that the elongate clasts are remnants of cross bed foresets that have been sufficiently lithified, eroded and broken off or dislodged close to their *in situ* state. The rounded biscuits are most likely a product of the elongate angular clasts after transport.

Figure 8.5 Angular elongate sandstone clasts identified as dislodged New Mountain Sandstone formation cross bed foresets preserved in the pale Altar Mountain Basal Conglomerate Lithofacies (AM-BCL). This particular clast was located very close to a protruded foreset thus being the likely parent area

8.2c Folkvanger Valley

A short time was spent in the Folkvanger Valley as the exposure of the HES was limited and quickly observed. The HES north of camp but is poorly exposed. It was identified due to the close association with the NMSst slump horizons earlier seen in the Nibelungen Valley. The HES in this area is irregular and undulated with small humps and hollows of up to 1m with a steady dip to the west.

Sites further east of camp provided continuous exposure of the HES as it formed a terrace where the field group could follow the HES laterally for over 1km.

The NMSst directly below the HES is extensively slumped north of camp with coherent isoclinal folds and convolute bedding within shallow but slightly trough cross beds. These involve both the whole cross bed set and within foreset folds and are commonly thicker than 1m but in some cases reach over 2m thick (see figure 8.6).

Figure 8.6 Slumped horizons in the New Mountain Sandstone Formation directly below the HES, Nibelungen Valley

A long lateral section was taken over the well exposed HES area west of camp to record the dip and any localised lateral changes in the area. Measurements showed a series of apposing dip directions indicating series of channels in a north-south direction. Investigation of the channels also showed a clear difference between AM-BCL thicknesses relative to their position. Noted were slight thinning (10-20cm) on the topographical highs and relative thickening in the troughs (20-50cm). No saw tooth pattern was seen at this location as the HES truncated the slump horizons.

8.2c Knobhead (Handsley Valley)

At this location the HES is no longer erosional and the overlying Altar Mountain Formation was deposited conformably on the New Mountain Sandstone (figure 8.6 location map, appendix A1). The contact at this site was identified by the first appearance or influx of feldspathic sediments as the erosional contact was no longer present. The feldspathic content fluctuated greatly over tens of meters indicating a rejuvenation of the source.

The NMSst underlying the conformable HES consists of the NM Interbedded Silt/Sandstone Lithofacies with very thick, low angle tabular cross beds of well sorted, fine to medium quartzose sandstones with thin green, fine sandstone to siltstone interbeds with *Skolithos* bioturbation. The siltstone horizons also appear sporadically in the fining up sequences within cross beds and between cross bed sets. These were often no thicker than a few millimetres but on occasion were as thick as 1-2cm. The horizons often form flame structures and elsewhere in the area appear to form drapes.

As mentioned in the previous chapter the trace fossil *Skolithos* varies greatly in its appearance in the upper New Mountain Sandstone. The *Skolithos* appears ~10-15 m below the first feldspar appearance and varies in abundance until disappearing 2 m below the HES and re-appearing 1 m above. The rapid change in grain size, with the initial influx of arkosic sediments appears to be the likely the reason. This could be an indicator that the environment became unfavourable for *Skolithos* in terms of the grain size and possibly the change of energy within the system at the time of deposition.

The horizon identified as the HES has grain size change from the well sorted, large low angle cross bedded medium quartzarenite to a granule/pebble lined feldsarenite. Furthermore, the initial influx of feldspar was approximately 5% but in places as high as 15%. The coarser sediments also displayed a marked change in foreset angle within the cross beds. Angles up to 25° were measured in the coarser units.

Dark green well laminated and lithified cobble sized ‘rip-up’ mudstone clasts were seen in the AM-BCL. The source of these rip-up clasts is unknown but show similarities in appearance of the Terra Cotta Siltstone Formation but with a different colour. This indicates a product of erosion elsewhere.

8.2d New Mountain

At the New Mountain location, the HES is also absent/conformable and the contact between the quartzose New Mountain sandstone and the overlying Odin Arkose Member of the Altar Mountain Formation was identified by the sudden influx of feldspar (figure location map, appendix strat column)..

The sediments in the uppermost NMSst consist of the NM Interbedded Silt/Sandstone Lithofacies. The sandstones are moderately well sorted, medium, cross bedded quartz sandstone as interchanging cross bedded and massive sandstone sequences with occasional very fine thin greenish very fine sandstone/siltstone drapes. The *Skolithos* in this location is introduced rapidly with the AM-BCL Lithofacies change and is soon abundant and exists for over 7m.

The initial introduction of feldspar is sudden with a percentage of 15% to 25% in places. This introduction of feldspar occurs with a change of grain size of very coarse sandstone with the granule clasts of feldspar. Also notable is the concentration of feldspar in granule lags along the cross bedded sandstone sequences after the initial influx. *Skolithos* quickly becomes sparse just before the HES feldspar influx horizon and is reintroduced once the initial coarser feldspathic sediments of the Odin Arkose fine to the normal Altar Mountain fine sandstones.

8.2e Rotunda

At Rotunda the HES is again absent and the conformable contact between the New Mountain Sandstone and the Odin Arkose is identified by the initial influx of feldspar and the change in abundance of the *Skolithos* trace fossil (figure 1.8, appendix A1).

The introduction of feldspar follows low angle tabular quartzarenites and forms low to medium angle trough cross bed sets. Again the feldspar is concentrated to the cross bed foresets and is commonly very coarse sand sized and sometimes granular.

The notable feature at this location for the sediments leading up to the HES is approximately 22m of abundant *Skolithos* before the appearance of any feldspar. The *Skolithos* initially appears in sparse horizons in well sorted, trough cross bedded, fine to medium quartz sandstone and becomes more abundant over approximately 6m. The influx of very coarse to granule feldspar is accompanied by the same grain size sub-well rounded quartz cross bedded successions. The influx of feldspar over the next 10m varies considerably from 0% to up to 20% present before becoming fully feldspathic. Again the *Skolithos* trace fossil appears to have been extinguished by the influx of coarse sediments and later reappears when finer successions occur in the above Odin Arkose Member.

8.3 Discussion

The Heimdall Erosion Surface throughout the field area varies from a relatively sharp erosive truncation of beds to a conformable contact defined by the influx of feldspar and grain size increase.

The HES truncates the quartzose New Mountain Formation at the Mt Boreas, Nibelungen Valley and Folkvanger Valley locations resulting in a saw tooth pattern and scattered, weathered biscuit shaped sandstone clasts. This suggests lithification of the New Mountain Formation sandstones before erosion. The cemented sandstone clasts preserved in the Altar Mountain Basal Conglomerate Lithofacies (Odin Arkose Member) are therefore suggested to be fragments of New Mountain Sandstone foresets and the roundness of such clasts represent the degree of reworking and weathering that the clasts experienced

The New Mountain Sandstone Formation sediments directly below the HES do not show any discoloration suggesting complete removal of the weathered horizon. Rounding and discoloration of the sandstone clasts suggests they sustained prolonged weathering in the soil profile and through reworking in the sedimentary environment. The HES forms a conformable succession at the Knobhead, New Mountain and Rotunda locations where the HES is observed as an influx of feldspar (concentrated to the low angle tabular cross bed foresets) and coarser grain size of quartz. This suggests that in the south the New Mountain Formation was not affected in the same way as what is seen in the north and only varied by the influx of fresher sediments.

The author suggests that the combination of erosion down to well lithified New Mountain Sandstone and the influx of coarse pebbles of locally eroded sandstone clasts and quartz and granular feldspar suggests a higher degree of erosion of the parent rock and therefore a significant drop in base level and resultant rejuvenation of feldspathic sediments. Also suggested is that the more conformable locations represent continuation of low angle beach environments due to the existence of low angle tabular cross beds and the concentration of coarser sediments along the foresets rather than in the northern locations where the lithified sediments were eroded and then re-initiated as pebbly beach environments

Opposing dip directions at the Folkvanger valley indicate channeling along the HES and resultant accumulation along the channel troughs. The channels trend in a north-south direction but insufficient plunge makes a direction of flow difficult. This however shows that the HES, at least at the Folkvanger Valley location, was channelized and suggests subaerial erosion in a fluvial setting before being reintroduced into a low angled beach environment. This is comparable to other trough cross bedded Odin Arkose sediments where the HES is conformable therefore suggesting the Odin Arkose in these areas was a short lived fluvial setting before moving back to a beach environment.

8.4 Conclusions

The HES represents a significant drop in base (sea) level and has resulted in the increased erosion of the source rock and a resultant increase of feldspar content and increase in quartzose sediment grain size; a rejuvenation scenario. The HES truncates the New Mountain Formation sediments in the north forming characteristic saw tooth pattern in the New Mountain Formation cross bedded sandstones. In one particular location (the Folkvanger Valley) channelizing of the HES suggests a significant lithofacies shift to a fluvial setting. In the south, however, the HES is seen as a conformable succession with an increase in grain size and a defined increase of granular feldspathic sediments indicating a continuation of coarse grained gravely beach environments. The areas where truncation is seen represents an intensive erosion period followed by the initial reintroduction of a pebbly beach environment, the AM-BCL or fluvial setting.

9. Chapter 9 - Altar Mountain Formation and Odin Arkose Member

9.1 Introduction

The Altar Mountain Formation directly overlies the Mountain Formation. It consists of interbedded subfeldsarenites and quartzarenites with an arkose to subarkose quartz sandstone basal member. It is bound at its base by the Heimdall Erosion Surface (HES) and at is overlain by the Arena Sandstone Formation. The basal member, the Odin Arkose Member, is a basal conglomerate which contains rounded to well rounded quartz pebbles and fragments of other lithologies. The basal conglomerate is overlain by trough and planar cross-bedded arkosic medium sandstone with *Skolithos* trace fossils and current flow directions trending from west to southwest (Barrett and Webb, 1973; Barrett and Kohn, 1975; McKelvey *et al.*, 1977; Bradshaw, 1981; Isaac *et al.*, 1995).

Paleoenvironmental interpretations were made by Barrett & Kohn (1975), suggesting the Altar Mountain Formation was deposited in a coastal-marine environment (due to the presence of siltstone and mud cracks), and Bradshaw (1981) suggesting a maximum marine transgression forming a shallow marine setting (due to trace fossil assemblages).

9.2 Lithofacies

9.2a Altar Mountain Basal Conglomerate Lithofacies (AM-BCL, Odin Arkose Member)

The AM-BCL is bound at its base by the Heimdall Erosion Surface (except where it is gradational), is overlain by the AM-GCL, measures up to 0.5m thick, and consists of a range of exotic clasts and feldspar and quartz granules to pebbles. The exotic clasts consist of biscuit shaped sandstone clasts with ranging roundness; a remnant of broken New Mountain Sandstone formation cross bed foresets, and other sandstones of unknown origin. The AM-BCL is poorly to very poorly sorted and grain size varies from medium sand matrix to cobble conglomeratic clast but predominantly pebble.

9.2b Altar Mountain Granule Cross Bedded Sandstone Lithofacies (AM-GCL)

The AM-GCL lies directly above the AM-BCL or on the upper NM-Tabular CSL (where the HES is gradational). It consists of low angle tabular cross beds that steepen depending on grain size and in some cases is interbedded with the AM-Tabular CSL. The grainsize is predominantly very coarse sand but has common concentrations of granular quartz and feldspar along cross bed foresets.

9.2c Altar Mountain Low Angle Tabular Cross Bedded Sandstone Lithofacies (AM-Tabular CSL)

The AM-Tabular CSL lies consists of low angle tabular cross beds and consists predominantly medium subfield arenites but ranging from coarse to fine. Cross beds are generally 1-2m thick and vary in dip from low angle to slightly higher in coarser beds. The feldspathic content in the AM-Tabular

CSL ranges throughout the stratagraphic column being more concentrated at the base and becoming sparser moving up through the section.

9.2d Altar Mountain Siltstone Lithofacies (AM-ZSTL)

The AM-ZSTL occurs only in the Folkvanger valley and consists of a 1-1.5m thick, dark green, well laminated, fissile, very fine grained sand to siltstone unit. It contains no trace fossils and appears to be laterally extensive within the field site. It is not observed elsewhere.

9.2e Altar Mountain High angled Trough Cross Bedded Sandstone Lithofacies (AM-Trough CSL)

The AM-Trough CSL consists of moderate to high angle trough cross bedded, moderately to well sorted quartz- to subfeldsarenites. The cross beds measure 1-2m commonly but on occasion measure up to 4m. Very few trace fossils are present in this lithofacies but scattered *Heimdallia*, *Skolithos* and very rare trackways similar to *Diplicnites* are observed. The AM-Trough CSL lies above the AM-Tabular CSL.

9.3 Facies Distribution and Relationships in Observed Sections

The Altar Mountain Basal Conglomerate Lithofacies (known as the Odin Arkose Member) was the main unit of interest as it directly overlies the Heimdall Erosion Surface. Data above the Odin Arkose Member lacks due to time constraints and poor exposure of outcrops. Variation of the OA-BCL was seen throughout the field in both composition and relation to the Heimdall Erosion Surface. In the northern locations (Mt Boreas, Nibelungen Valley and Folkvanger Valley) the composition includes sandstone biscuit shaped clasts, granule feldspar, pebble vein quartz and a range of other exotic quartz sandstones, and possibly rhyolite fragments. In the south however (Knobhead, New Mountain and Rotunda), the AM-BCL consists of an influx of feldspar and a slight increase in quartz grain size, represented by granule cross bedded lithofacies (the AM-GCL). The upper Altar Mountain Formation was only recorded in two locations, Knobhead (Handsley Valley) and Rotunda. The lower Altar Mountain Formation, the Odin Arkose Member, however was recorded at all sites where the Heimdall Erosion Surface (HES) was observed.

9.3a Mt Boreas

The Altar Mountain Basal Conglomerate Lithofacies (AM-BCL) at Mt Boreas is 20-30cm thick and consists of a conglomerate with a matrix of very coarse feldsarenite sandstone with sub-rounded to well rounded quartz and sub-angular to angular feldspar granules. Also present are a number of pink biscuit-shaped pebble to cobble clasts of well sorted fine to medium quartz sandstone of a similar composition to the New Mountain Sandstone Formation (see figure 9.1). The pink discoloration suggests prolonged weathering or diagenetic alteration of the clasts.

Figure 9.1 Odin Arkose Basal Conglomerate Lithofacies on the Heimdall Erosion Surface containing pink sandstone biscuits both intact and fragmented, Mt Boreas

9.3b Nibelungen Valley

The AM-BCL in this area ranges in thickness from 2cm (a single layer of well rounded quartz pebble, see figure 9.2) to 20cm. The thickest portions of the AM-BCL occur where there are large elongate slabs of well sorted sandstone most likely broken underlying New Mountain Formation cross bed foresets. The rounding and discolouration of the clasts may be due to prolonged weathering or diagenetic alteration of the angular slabs. Some other exotic clasts were observed but cannot be correlated to any local sandstone units and therefore are interpreted as sourced from outside the boundaries of the field area.

A notable feature of the AM-BCL in this area is the even distribution of the pebble conglomerate along the surface of the HES. Note that in this area the HES has no saw toothed erosional contact with the underlying New Mountain Formation and is relatively flat.

Figure 9.2 Well rounded quartz pebble in the Odin Arkose Basal Conglomerate Lithofacies

New Mountain sandstone clasts are scattered and relatively rare overall but locally abundant in places The sandstone clasts range in appearance from well rounded 2-15cm flat biscuits to angular elongate slabs up to 1m long (see figure 9.3). The author suggests that the angular elongate clasts are remnants of cross bed foresets that have been sufficiently lithified to retain their shape, then eroded and broken off or dislodged close to their *in situ* location. The rounded biscuits therefore indicate abrasion.

Figure 9.2 Dislodged New Mountain Sandstone formation cross bed foresets preserved in the pale Odin Arkose Basal Conglomerate Lithofacies (OA-BCL).

9.3c Folkvanger Valley

The Altar Mountain Basal Conglomerate Lithofacies (AM-BCL) ranges between 0.2-0.5m thick and was again comprised of biscuit shaped quartz sandstone fragments ranging from rounded to angular, sub-rounded to well rounded quartz pebbles, and angular to subrounded feldspar crystal granules. The sandstone clasts are rare overall but are concentrated locally in some areas whilst the quartz and feldspar sediments are well spread.

Many of the sandstone clasts contain thin laminations. This is very similar to what is seen in the New Mountain Sandstone Formation cross bed foresets. Imbrication of the clasts also indicates sustained currents within the water column (See figure 9.3).

Figure 9.3 Sediments directly above the HES south of camp showing laminated biscuits of quartz sandstone and slight imbrications, Folkvanger Valley

The HES and the AM-BCL was observed laterally along a well exposed area to identify any changes in HES dip or AM-BCL thickness. Measurements showed a series of apposing dip directions indicating series of channels in a north-south direction. Investigation of the channels also showed a clear difference between AM-BCL thicknesses relative to their position. Noted were slight thinning (10-20cm) on the topographical highs and relative thickening in the troughs (20-50cm). This indicates channelizing of the HES and resultant accumulation along the troughs. This could indicate a deepening in the water column an resultant channelization.

Pebble counts along the lateral section show a high percentage of reworked quartz grains, quartz sandstone clasts and quartzite clasts. Also seen are clasts of white, very fine grained rocks that are identified as rhyolite fragments (e.g. Savage, 2005; Gilmer, 2007).

9.3d Knobhead (Handsley Valley)

In the Handsley Valley there are no erosional HES and the contact is instead identified by the influx of feldspar. The identification of the contact proved difficult as the initial influx of feldspar was slight before becoming predominant. The grain size of feldspar was predominantly granular and therefore is classified as the AM-GCL with no AM-BCL. The AM-GCL and the AM-CSL alternated over tens of meters. Close to the initial influx of feldspar occur dark green, well laminated, cobble sized mudstone clasts. The source of these mudstone clasts is unknown but show similarities in appearance to the Terra Cotta Siltstone Formation but with a different colour. It is suggested that these are most likely from a Terra Cotta equivalent in the upper reaches of the New Mountain Formation not seen in this area

The AM-GCL exhibits characteristic large low angle cross bedded medium quartzarenite sandstone to a granule/pebble lined subfeldsarenite cross beds. The initial influx of feldspar was noted as approximately 5% but in places as high as 15%. The coarser sediments also display a marked change in foreset angle within the cross beds reaching angles up to 25° in the coarser units. The AM-Tabular CSL consists of low to moderate angle, well sorted, tabular cross bedded sandstones with varying concentration of feldspar. Coarser sand quartz and feldspar is concentrated to the cross bed foresets.

The AM-GCL exhibits characteristic large low angle cross bedded medium quartzarenite sandstone to a granule/pebble lined subfeldsarenite cross beds. The initial influx of feldspar was noted as approximately 5% but in places as high as 15%. The coarser sediments also display a marked change in foreset angle within the cross beds reaching angles up to 25° in the coarser units. This indicates a steepening of the shore face but not necessarily a deepening of the water column. It is therefore suggested that in this location the Altar Mountain Formation environment progresses from shallower to steepening beach face as a result of the coarse grain size.

9.3e New Mountain (Windy Gully)

At this location the HES is not represented by a truncation of the New Mountain Sandstone but an influx of arkosic sediments. The initial introduction of feldspar is more sudden than what is seen in Knobhead with a percentage of 15% and up to 25% feldspar in places. This introduction of feldspar, identified as the AM-GCL, coexists with the change and decline in abundance of the *Skolithos* trace fossil and the change of grain size from mostly very coarse sand with the granules predominantly being feldspar. The AM-GCL measures 6.5m and consists of moderate to low angle tabular cross beds. The concentration of feldspar exists predominantly along the cross bed foresets after the initial influx. Only the AM-GCL was measured in this area.

9.3f Rotunda

At the Rotunda camp site the Heimdall Erosion Surface was again identified as not erosional and seen by the an influx of very coarse sand to granule feldspar and sub-well rounded quartz cross bedded successions. The AM-GCL occurs over 10m and consists of interbedded successions of low angle tabular quartz arenites and steeper tabular cross bedded very coarse sand feldsarenites. Again the *Skolithos* trace fossil appears to have been extinguished by the influx of coarse sediments and later reappears when finer successions occur in the above Odin Arkose Member.

Following the AM-GCL is 24m of low angle both tabular and slightly trough cross bedded subfeldsarenites, identified as the AM-Tabular CSL. The cross beds measure up to 1m thick but are predominantly thinner through the section. These cross bedded successions have no trace fossil assemblages. The slightly trough cross bedded subfeldsarenites could indicate a partial channelizing of sediments possibly due to a slight deepening of the water column.

9.4 Discussion and Interpretations of Depositional Settings

Previous paleoenvironmental interpretations of the Altar Mountain Formation include Barrett & Kohn (1975), suggesting the Altar Mountain Formation was deposited in a coastal-marine environment (due to the presence of siltstone and mud cracks), and Bradshaw (1981) suggesting a maximum marine transgression forming a shallow marine setting (due to trace fossil assemblages).

The Altar Mountain Formation described here shows distinct characteristics similar to the Windy Gully and New Mountain Sandstone Formations, especially with low to moderately angle tabular and trough cross bedded sandstone lithofacies relationships. Again the progression from low-angle tabular to moderate to high-angle trough cross beds indicates a progressive deepening of the water column from a beach to a shallow marine environment. The Altar Mountain Formation sediments are generally coarser with the AM-GSL measuring approximately 10m followed by tens of meters of AM-Tabular CSL. The AM-GCL suggests the formation of very coarse sandy beach environments followed by a continuation of better sorted medium sand beach setting. The slight steepening in cross bed dip is consistent with the increase in grain size suggesting a steeper beach face with the influx of coarser sediments. The coarser subarkosic sediments suggest a rejuvenation of source resulting in the sudden influx of sediments.

Also observed is the AM-ZSTL, a 1-1.5m thick dark green siltstone. The well laminated fissile nature of this lithofacies is consistent of an upper Terra Cotta Fissile Dark Lithofacies (see chapter 5.2b) that has been interpreted as a short lived mud flat or salt marsh environment. It is therefore suggested that the AM-ZSTL was a short lived mud flat between the AM-Tabular CSL low angle beach environment, a small lithofacies and environmental shift.

The range of exotic clasts in the AM-BCL also suggest a large drop in base level as many of the clasts seen are of unknown and not of local origin (within the field area). The range of biscuit shaped clasts has been determined as broken New Mountain Formation cross bed foresets that have been progressively reworked. The amount of reworking has been determined by the roundness, elongation and degree of pink coloration of the clasts.

The Folkvanger Valley shows channelization of the HES surface suggesting concentration of erosion. This coexists with variation in thickness of the AM-BCL along the channels and bunds. This could therefore suggest an isolated fluvial setting with channel fill that was then succeeded by the low angle beach cross bedded sediments. The erosional channelization of the HES and subsequent tabular cross bedded channel fill therefore indicates a short lived fluvial setting. This was followed by low angle tabular cross bedded beach sediments of the AM-Tabular CSL. The presence an isolated fluvial setting indicates a significant facies and environmental shift and therefore a significant drop in relative base level and concentrated erosion.

Where the HES is gradational (in the south) the influx of coarser sub to arkosic sandstones (the AM-GCL) suggests an influx of coarser and fresher sediments from a rejuvenation scenario. The coarser sediments would have formed a steeper and coarser grained sand to granular beach face. The interbedding of coarser and then better sorted and finer sediments suggests an interfingering relationship with fresher rejuvenated source sediment and older reworked quartzose sandstones. The slight trough cross beds higher in the stratigraphic column suggest a slight deepening of the water column and possible channelization of sediments.

9.5 Conclusions

The Altar Mountain Formation is interpreted as a progression from coarse gravelly to low angle beach environments with confined intermittent mud flat deposits. This then proceeds into a possible shallow marine environment with slight channelization of sediment identified by slight trough cross bedding. At one location, the Folkvanger Valley, channelized erosion followed by fill and tabular cross bedded sandstones suggests a shortly lived fluvial environment before proceeding into low angled coarse to gradually fining sandy beach setting. Also in the Folkvanger valley were localized (but laterally consistent in the field site) siltstone lenses suggesting short lived mud flats within the low angle beach environments. In the south the AM-Tabular CSL stays low angle but ranges to slightly trough cross bedded in characteristic but this still suggests a beach environment overall.

10. Chapter 10 - Provenance

10.1 Introduction

Little is known in terms of provenance for the Beacon Supergroup sediments due to its prominent quartz content and lack of body fossils. The age of the source rock can be determined by crystallization age of the rare zircon crystals obtained by LA-ICP-MS from samples above and below the Heimdall Erosion Surface (The upper and lower Odin Arkose Member and New Mountain Sandstone respectively (see Methodology, Chapter 1). A change in zircon ages would indicate a change of source rock and therefore sediment source change, exhumation/rejuvenation or significant deeper erosion of the same source. Evidence of source change can also be complimented with basic sample composition and QFL data and supported by any significant changes in paleocurrent directions. Four samples were taken particularly in the Handsley Valley for zircon analysis due to constant well exposed Beacon sediments throughout the relevant stratigraphic area. The following chapter presents and discusses results from the LA-ICP-MS dating and cathodoluminescence images of zircon grains from the 4 samples, clast and point count data and discussion of the changes in quartz vs. feldspar concentrations throughout the observed formations.

10.2 LA-ICP-MS

LA-ICP-MS U-Pb age dating was performed on the detrital zircons from four samples at the Knobhead (Handsley Valley) location (see figure 10.1). The dates obtained provide insight to the origin of the source rock. The age dating was performed at the Research School of Earth Sciences, Australian National University (ANU) in conjunction with Dr Michael Palin, Otago University (see Methodology, Chapter 1)

Sample	Field site	GPS	Formation
T50	Mt Handsley	S77° 55.503’ E161° 37.263’	Base of NMS
T53	Mt Handsley	S77° 55.829’ E161° 37.665’	NMS Below HES
T51	Mt Handsley	S77° 55.829’ E161° 37.665’	Odin Arkose above HES
T63	Mt Handsley	S77° 53.796’ E161° 40.291’	Top of Odin Arkose

Figure 10.1: Description and location of samples used for LA-ICP-MS

5.2.2 Results

All of the age peaks in the Knobhead (Handsley Valley) location above and below the HES show strong peaks of 560 to 620Ma; and scattered peaks between 980Ma and 1220 Ma (for samples T50,51,and 63) in age. Such a similarity in ages suggests that there was no sediment source change over the period that the HES occurred thus indicating a minor rejuvenation scenario

5.2.3 Interpretation

Allibone *et al* (1993, 1993a) and Allibone and Wysoczanski (2002) divide the Granite Harbour Intrusives into suites based on date of emplacement and composition. DV1a suite was emplaced between 490 and 589 Ma; DV1b suite was emplaced around 490 Ma and DV2 suite was emplaced between 455 and 489 Ma. The zircon data fits within the DV1a emplacement age but the older zircon ages preceed both the Granite Harbor Intrusives and the second metamorphism D2 age of the Koettilitz Group (670Ma).

The first peak and second broader peak between (980Ma and 1220Ma) is also consistent with detrital zircon ages of the Neoproterozoic Skelton Group which is dominated by a ca. 1300-950Ma date range (Wysoczanski & Allibone, 2004). The zircon age signatures and other smaller age peaks in Wyscoczanski & Allibone (2004) are also comparably similar strengthening thisinterpretation of the source (see Allibone & Wysoczanski, 2002).

An absence of the broad peak in sample T53 (see figure 10.2), taken from the upper New Mountain Sandstone Formation (low angle tabular cross bedded quartzarenite sandstones), was the only sample dated free of feldspar. The absence of the older broad peak suggests that the older sediment source from the Skelton Group was likely to have ceased approaching the end of the New Mountain Sandstone Formation sedimentation. The author suggests that this was due to the lack in base level drop between the Skelton Group source and the depositional setting and therefore the only sediment source was from the younger DV2a Granite Harbour Intrusive source.

In conclusion, the sediment source for the New Mountain Sandstone and Altar Mountain Formations did not change across the unconformities and was predominantly sourced from the Neoproterozoic Skelton Group and the Granite Harbour Intrusives, both locally present. In addition, the upper New Mountain Formation sediments did not receive any sediment from the Skelton Group and was therefore entirely sourced from the DV2a Granite Harbour Intrusives.

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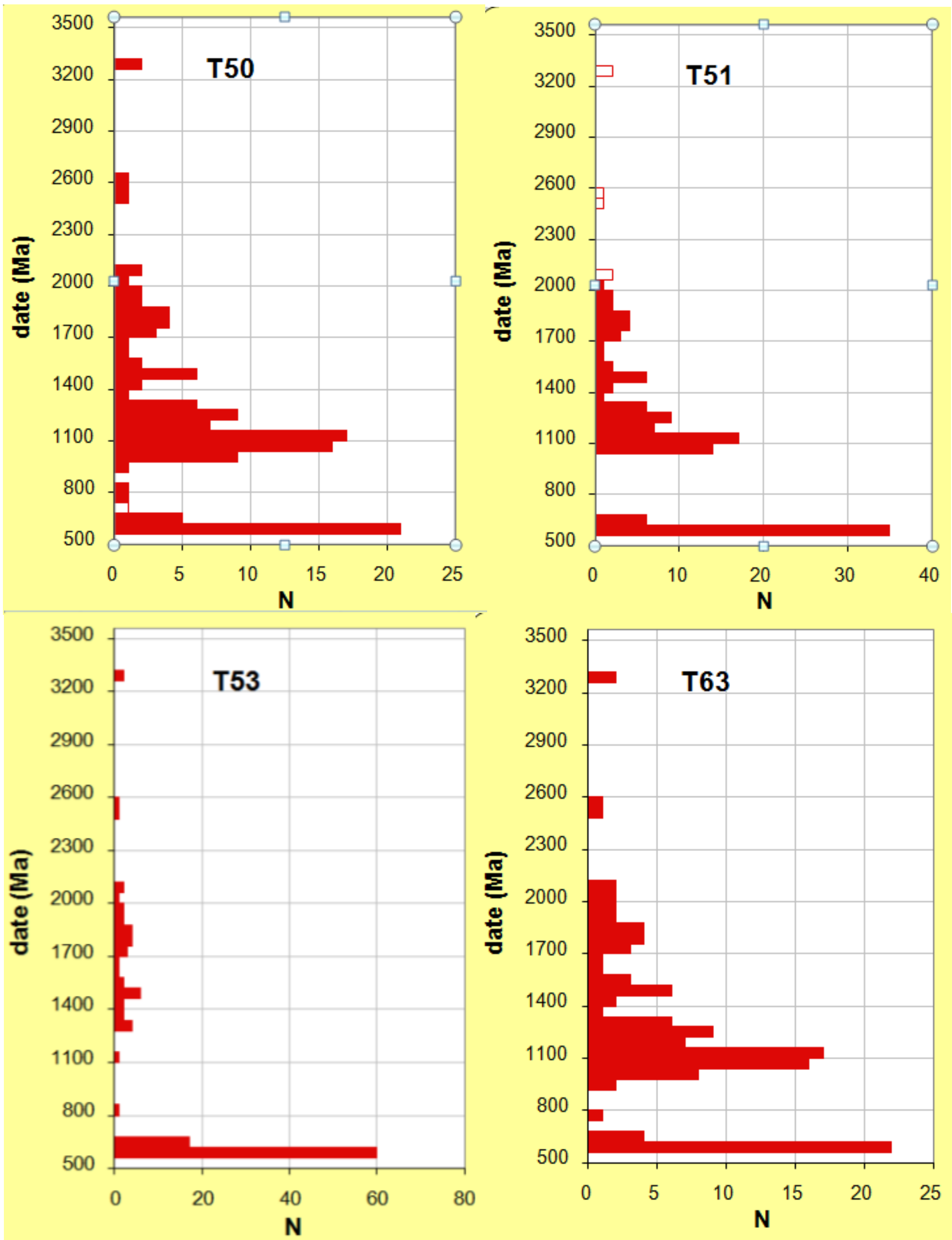

Figure 10.2 Zircon age plots of samples taken above and below the HES, Knobhead (Handsley Valley)

10.3 Cathodoluminescence

High resolution SEM-CL images were taken to obtain a clear view of zoning within the zircon crystals. This was concentrated where the LA-ICP-MS shots hit in respect to the zoning as the outer rings at the crystal tip were being targeted.

The zircons show typical zoning and have an irregular to rounded shape often close to their original crystal shape, but in some cases are broken. The zoning of the zircons is important as they indicate if the core of the crystal is older (inherited), which is seen by the cross cutting relationships within. Some cross cutting was seen indicating the presence of inherited cores. A majority of the zircons had distinct age rings and therefore were most likely to give data of the youngest phase of crystallization. The shot points for the LA-ICP-MS U-Pb dating were concentrated at the crystal point as it was where the best preserved age rings exist.

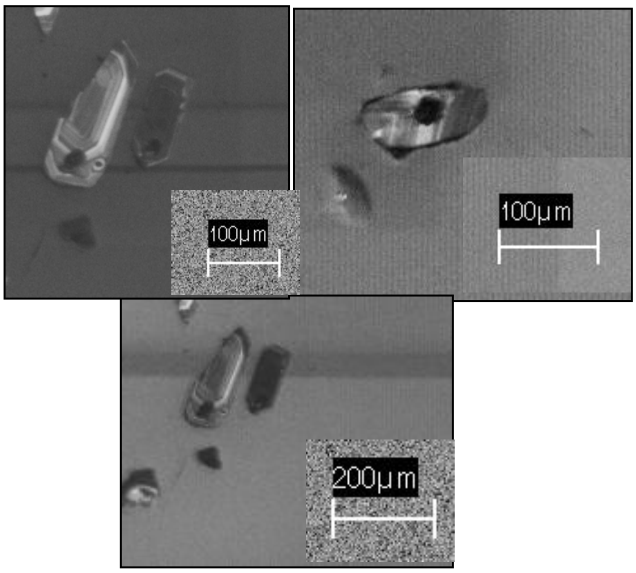

Figure 10.3 SEM-CL images of zircon crystals and shot points for LA-ICP-MS analysis

10.4 Quartz vs. Feldspar

This section describes and discusses the relationship between concentrations of feldspar in the felds to subfeldsarenites of the New Mountain and Windy Gully Sandstone Formations and the Odin Arkose Member of the Altar Mountain Formation. .

10.4a Results

Thin section point counts, of a range of samples taken in the field, show a trend of lessening feldspar content between the upper and lower Windy Gully and New Mountain Sandstone Formations (see figure 10.4). the data shows a distinct loss of feldspar content in the upper reaches of the formations and trend towards subfields- to pure quartz arenites. The New Mountain Sandstone Formations is a prime example as the lowermost reaches are relatively feldspar rich whilst the upper cross bedded sandstones become pure quartzarenites. The Altar Mountain Formation is also comparible with a high concentration of feldspar at its base and decrease higher in the stratagraphic column.

10.4b Interpretation

The Windy Gully Sandstone and New Mountain Sandstone are very similar in physical appearance but differ in feldspar content. The Odin Arkose Member is also included due to the initial influx of feldspar rich sediments directly after the HES horizon.

The Windy Gully Sandstone Formation is predominantly subfeldsarenite whilst the New Mountain is only feldspathic towards the base before becoming almost purely quartzarenite. Both formations are predominantly cross bedded throughout and have varying successions of bioturbation.

The noticeable difference between the WGSst, the NMSst and the AM-BCL (Odin Arkose Member) environments is the basal contact; the WGSst basal contact is the Kukri Erosion Surface on on regional basement, the NMSst basal contact is the Windy Gully Erosion Surface, and the Altar Mountain is bound at its base by the Hiemdall Erosion Surface.

10.4b Discussion

Observed in the field; of later interpretation of point counts and stratigraphic columns, is a higher concentration of feldspathic sediments in the lower successions of the formations and a gradual lessening through the stratigraphic column. The coarser feldspathic sediments have also been noted to be concentrated along low angle tabular cross bedded sandstone lithofacies (interpreted as low angle beach and shore face environments). A notable feature of both formations is the common concentration of feldspar grains, especially coarser, along the cross bed foresets. This is a likely situation due to the density differences between quartz and feldspar resulting in concentration and indicates a degree of reworking to form such concentration horizons. The fact that the percentage of feldspar content in the sediments is confined to the basal units of each formation suggests that it is stratigraphic rather than lithofacies dependent. This is seen especially in the upper and lower NM-CSL as the lower contains scattered horizons and in places is slightly feldspathic whilst the upper is predominantly a pure quartz arenites.

Provenance analysis of the rare zircon crystals has proven that the source of sediment has not changed over the period of the Heimdall erosion surface and throughout the NMSst or Altar Mountain Formation. The author suggests this indicates a rejuvenation scenario where the same sediment source is reactivated due to relative sea level fall and therefore initiates increased erosion. If the source body is relatively homogeneous and deposition was consistent with no sea level change, the supply and concentration of feldspar would remain unchanged. This however is not the case and differing erosional and depositional rates would result in variations in the concentration of more unstable and stable minerals, for example feldspar and quartz respectively.

The New Mountain Sandstone, where feldspar is only present at the base and absent up section suggests an initial drop in base level to transport the feldspar quickly to the source but with sea level rise this was slowed and the feldspar had sufficient time to be weathered out. In contrast, the Windy Gully Sandstone Formation, where the feldspar is present throughout but gradually decreases upwards, indicates a sustained drop in base level sufficient to quickly transport feldspar throughout deposition. This is also seen in the Odin Arkose Member, where the feldspar increases dramatically after the HES from a sustained drop in base level and initiation of erosion. This indicates that the feldspar was transported and deposited quickly after the erosional period and therefore not giving sufficient time for the weathering out of feldspar.

10.4c Conclusions

The differing concentration of feldspar in the New Mountain, Windy Gully Sandstone and Altar Mountain Formations is a result of the weathering during transport and reworking throughout deposition. This has a direct correlation with the intensity of the erosion surfaces directly underlying and the differing degree of chemical and physical weathering through transportation and deposition. The greatest concentration of feldspar was observed in the lower most regions of each formation in predominantly low angle cross bedded beach environments, directly above the associated erosion surfaces.

In the New Mountain Sandstone Formation especially, the author suggests the transportation and reworking in the upper units were sufficient to completely remove the feldspar and the subsequent clay minerals were removed as clay minerals; thus resulting in an almost pure quartzose succession. Any feldspar that was present in the upper parts of both the New Mountain and Windy Gully Sandstone Formation was concentrated in the cross bed foresets. The author suggests that the low angled cross bedded beach berm deposits would have concentrated the feldspar by wave action and the higher angled trough cross beds would have concentrated the feldspar along the channels through the difference in density of the feldspar mineral itself.

10.5 Sediment Composition

Clast and pebble counts were performed on a range of locations and samples were taken from the field during the season for later analysis by point counts. A number of samples have been plotted into QFL diagrams to determine the likely source and support the other provenance data (see figure 10.4).

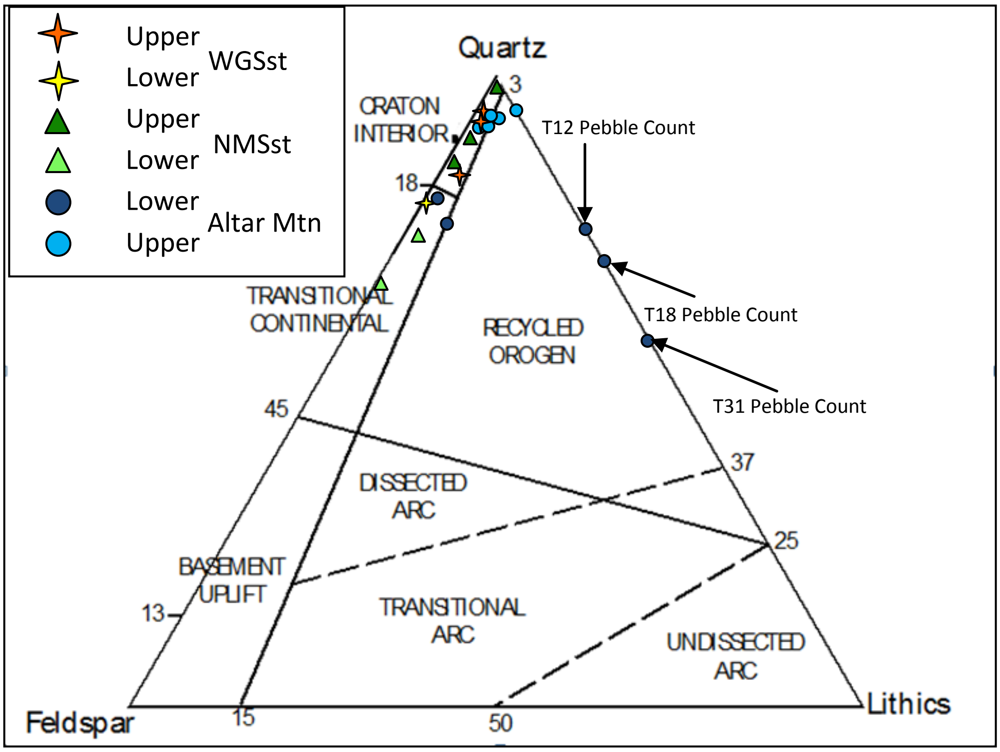

Figure 10.4 Tectonic discrimination diagrams of Dickinson *et al* (1982) from point and pebble counts of sandstones taken from the Windy Gully Sandstone, New Mountain Sandstone and Altar Mountain Formations

Tectonic discrimination diagrams of Dickinson *et al* (1982) suggest that the source rock of the samples taken from the upper portions of the sandstone formations come from craton interior whilst the lower portions come from transitional continental origin. This can suggest both either uplift or sea level fall, in summary, a relative sea level fall. In addition, some of the upper measures lay boarder line recycled origin along with the pebble count data which is expected as they consist of a high proportion of lithics and have identified rip up clasts of the underlying units, indicating recycling of previous sediment.

10.6 Paleocurrent Directions

Cross beds, ripple cross-laminations and trough channel axes were measured throughout the stratigraphic sections for information on changing paleocurrent directions. This data was then divided into the appropriate formations to determine any current direction changes throughout the deposition of the lower Beacon Super Group. Cross bed foresets were the most common structures measured and a majority of the main bed structures were either flat lying or very shallow in dip therefore the foreset dips seldom needed any correction for post depositional tilting. Paleocurrent measurements were confined to the Windy Gully Sandstone and the New Mountain Sandstone. The Altar Mountain Formation was generally coarser grain size making cross beds difficult to measure. Two measurements were taken from the Altar Mountain Sandstone but these are not representative of paleocurrent direction.

10.6a The Windy Gully Sandstone Formation

The Windy Gully Sandstone Formation trends predominantly between west and northwest (see figure 10.5). This suggests that there was again a north south shoreline at the time of Windy Gully Sandstone Formation deposition and that progradation of the sediments were predominantly towards the west. There is also a north-south component but only single data set measurements indicating long shore current effects. This is a similar situation to what is seen in the New Mountain Sandstone

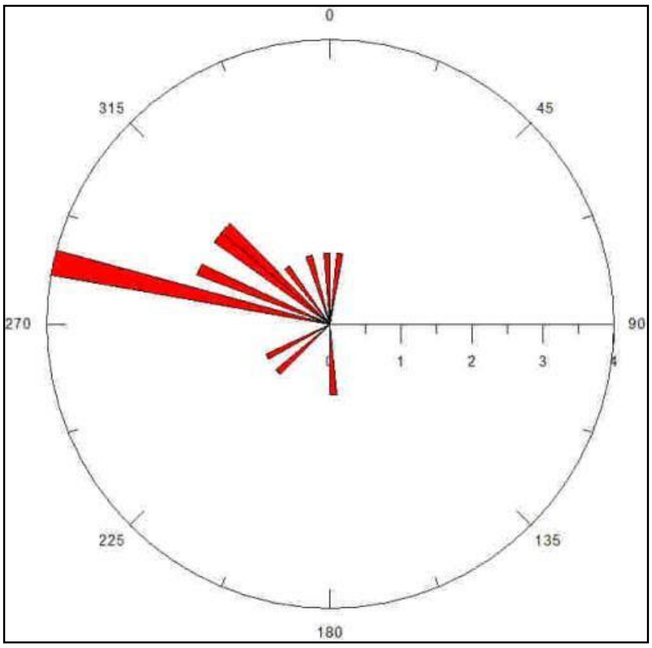

Figure 10.5 Paleocurrent directions of the Windy Gully Sandstone Formation

10.6b The New Mountain Sandstone Formation

Paleocurrent directions of the New Mountain Sandstone Formation show two separate directions; one trending west and the other trending more north to almost northwest (see figure 10.6). This suggests a north-south coastline with westward progradation with north trending long shore currents in the shallow marine trough cross bedded sandstones.

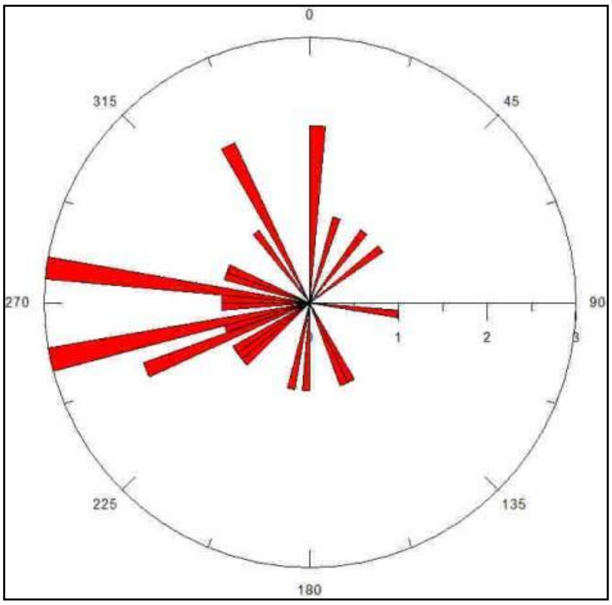

Figure 10.6 Paleocurrent directions of the New Mountain Sandstone Formation

10.7 Interpretation and Discussion

The sediment source for the New Mountain Sandstone and Altar Mountain Formations remains unchanged throughout deposition. The probable source is the Neoproterozoic Skelton Group, a local source but also has a DV2a Granite Harbour Intrusives component. The upper New Mountain Sandstone Formation however has a lack of date signature for the Skelton Group indicating it was cut off at this time, most likely due to insufficient base level drop.

The feldspathic content of the Windy Gully, New Mountain Sandstone and Altar Mountain Formations also decreases moving through the stratigraphic column. The upper New Mountain Sandstone in particular becomes pure quartz arenite indicating a lack of rejuvenated source sediment; this is consistent with a lack of Skelton Group age data for the upper NMSst sample (sample T53, figure 10.2) indicating no source supply from this particular source.

Tectonic discrimination diagrams of Dickinson et al (1982) suggest that the source rock of the samples taken from the upper portions of the sandstone formations come from a craton interior source whilst the lower portions come from transitional continental origin or recycled origin. This can suggest both either uplift or sea level fall, in summary, a relative sea level fall. The recycled origin is expected directly after the erosion surfaces as the eroded sediments were a majority component of the basal conglomerates.

Paleocurrent data suggests a trend towards the east with some northern components most likely due to longshore currents in the trough cross bedded sandstones. The paleocurrent data also indicates prominent sediment progradation towards the west and with the northern component longshore currents driving sediments 90 degrees to the shoreline. This could therefore suggest a north-south coastline with sediment from the source coming in from the east.

Both the Neoproterozoic Skelton Group and DV2a Granite Harbour Intrusives are local source and therefore a likely candidate for the supply of sediments to the area. The Skelton Group appears to be the dominant source except where it is cut off from the uppermost New Mountain Sandstone Formation. The DV2a Granite Harbour Intrusives also fit within the younger zircon date age range and therefore were also a likely source rock.

11. Chapter 11 – Sequence Stratigraphy

11.1 Introduction

A sequence in sequence stratigraphy is defined as a sequence composed of a relatively conformable succession of genetically related strata bound at its top and base by unconformities, or their correlative conformities. The sequence concept assumes eustatic sea level changes or relative base (sea) level changes to be the driving force of the stratigraphic sequence (Mitchum, Vail and Sangree, 1977). A sequence represents a single cycle of deposition bounded by non marine erosion, and deposition during one significant cycle of rise and fall of base level (Boggs, 2001). Sequence stratigraphy will therefore be used to elaborate stratigraphic cycles in the observed Taylor Group sediments in the Dry Valleys. It will also be used to provide a 3-dimensional interpretation of vertical and lateral lithofacies relationships following Walther's law, in this case in a shallow marine and shore face environment (see figure 11.1).

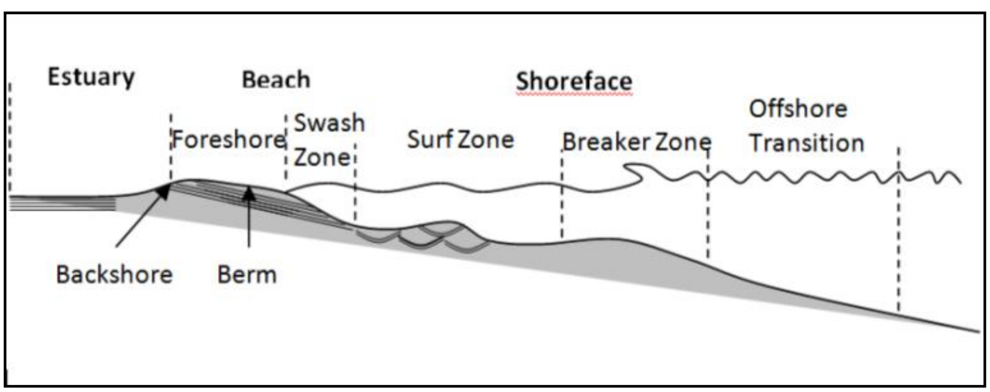

Figure 11.1 Schematic diagram of shallow marine setting comparable to the lower Taylor sediments (adapted from Boggs, 2001)

11.2 The Lower Taylor Group

The lower Taylor Group deposits contain at least three sequences with relatively conformable successions of sediments bound between erosion surfaces or correlative conformities (sequence boundaries). The three main erosion surfaces are the Kukri, Windy Gully and Heimdall Erosion Surfaces. The conformable successions are the Windy Gully, the New Mountain and the Altar Mountain Formations. This can be combined with the interpretation of depositional environments showing relative sea level changes and the resultant systems tract and lithofacies shifts within the sequence stratigraphy cycle. The erosion surfaces act as a key start point as they indicate low stands where base level is at its lowest and thus only subaerial erosion is present. This can be combined with the interpretation of the overlying basal conglomerates and erosion characteristics of the erosion surfaces to determine the intensity of the erosion and base level drop.

The following sections will briefly describe the progression of each sequence and interpret their relevant systems tract. This will follow a progression through changes in sea level over the thickness of the observed lower Beacon Supergroup.

11.3 Sequences and Sequence Boundaries

The following sections briefly describe the erosion surfaces and formations as sequences. The sequences will then be described in terms of sequence stratigraphy and the associated systems tracts to eventually show a single and a combined set of sequence stratigraphy cycles.

11.3a Sequence Boundary - The Kukri Erosion Surface

The Kukri Erosion Surface represents the exhumation of the Ross Orogenic Belt forming a high energy and high relief granitic erosional basal contact. In it's latest stages, the Kukri Erosion Surface existed as a rugged wave dominated marine shore face, similar to sites seen today on the West Coast of the South Island, New Zealand. This represents a sustained low relative sea level and therefore a systems boundary. The Kukri Erosion Surface represents the basal bounding surface on which the first sequence (SU1) was deposited.

11.3b Sequence 1 (S1): The Windy Gully Sandstone and Terra Cotta Siltstone Formations

The Windy Gully Sandstone Formation (WGSst) and Terra Cotta Siltstone Formation (TCzst) are bound between the underlying Kukri and the overlying Windy Gully Erosion Surfaces (see figure 11.2).

The Windy Gully Sandstone Formation (WGSst) and the lithofacies within represent the rise in relative base (sea) level within the first sequence. The author suggests that the WGSst represents a transgressive to high stand to regressive systems tract where it gradationally meets the Terra Cotta Siltstone Formation, the latest stage of a forced regressive systems tract.

The WGSst is split into five lithofacies consisting of: the Windy Gully Basal Conglomerate Lithofacies (WG-BCL), a varying thickness of clast and matrix supported boulder conglomeratic basal rubble with a very coarse sand to granule arkosic matrix. The author suggests that the WG-BCL formed the initial sedimentation and progradation forming a rugged rocky shore face which progressed into a coarse gravelly beach setting (the WG-BCL). This lithofacies represents the earliest stages of a transgressive systems tract.

The Windy Gully Granule Cross Bedded Lithofacies (WG-GCL) consists of a very coarse sand to granule cross bedded feldsarenite sandstone. This represents a coarse continuation of a beach environment with deposition of sediments keeping up with the relative sea level rise. This is therefore also part of the transgressive systems tract.

The Windy Gully Interbedded Siltstone and Cross Bedded Sandstone Lithofacies (WG-IZCL), only seen in the Nibelungen Valley, consists of interbedded units of well laminated very fine sandstone to siltstone beds and well sorted, low angle, tabular cross bedded, medium to fine sand subfeldsarenites. This represents a tidal flat/estuarine environment most likely protected by a barrier bar of the overlying WG-Tabular CSL. This lithofacies shows a tidally effected shallow water lithofacies that preceded the beach setting. This is also included in the transgressive systems tract as a lateral facies to the rugged rocky shore face and gravelly beaches of the WG-BCL and WG-GCL.

The Windy Gully lower Low Angle Tabular Cross Bedded Sandstone Lithofacies (lower WG-Tabular CSL) consists of a series of low angle, tabular cross bedded, well sorted, bioturbated, fine to medium sand subfeldsarenites. This represents a low angle beach setting under a continuing rise in base (sea) level and is included into the transgressive systems tract. All of the above lithofacies formed as sediment deposition with a steady sea level rise where the sediments ‘kept up’ with the relative sea level rise.

The Windy Gully High Angle Trough Cross Bedded Sandstone Lithofacies (WG-Trough CSL) is a series of higher angle, trough cross bedded, and well sorted, fine to medium subfeldsarenites. This represents a deepening in the water column and transition into a channelized shallow marine environment interpreted as occurring in the surf to breaker zone. This represents a high stand systems tract as the water depth is at its greatest. Note that the WG-Trough CSL is bound between the upper and lower WG-Tabular CSL.

The Windy Gully upper Low Angle Tabular Cross Bedded Sandstone Lithofacies (upper WG-Tabular CSL) is physically very similar to the lower WG-Tabular CSL and consists a series of low angle, tabular cross bedded, well sorted, bioturbated, fine to medium sand subfeldsarenites. This represents a regressive systems tract as either sediment progradation or a drop in sea level is now shallowing the water column and moving back into a beach setting. In the sedimentary record this will show a relative sea level fall.

The Terra Cotta Siltstone Formation (TCzst) and the lithofacies within represent the final stage of SU1, a regressive systems tract where maximum sea level fall has occurred and forced a shallowing in the water column. The TCzst is split into two lithofacies . the first is the Terra Cotta Sandy Mottled Lithofacies (TC-SML), a well laminated and mottled very fine sand to siltstone with varying degrees of bioturbation. This is interpreted as deposited in a tidally effected estuarine or lagoon environment. the second Terra Cotta lithofacies is the Terra Cotta Fissile Dark Lithofacies (TC-FDL), a very well laminated, fissile, very fine sand to siltstone interpreted as a very low energy and not tidally effected salt marsh or mud flat. The Terra Cotta Siltstone Formation was likely to be deposited in an estuary or lagoon protected by the low angle beach berm environment of the upper WG-Tabular CSL assuming facies succession of Walter's Law.

In summary, the extensive erosion of basement on the KES was due to a sustained relative sea level low. A relative sea level rise initiated deposition and a transgressive systems tract gradually extending beach sediments (and isolated tidal flat settings in places) seaward forming the WG-BCL, GCL, IZCL and the lower Tabular CSL.

Continued relative sea level rise resulted in further transgression and a gradual deepening of the water column. This resulted in a shallow marine environment and facies shift into channelized trough cross bed sequences, the WG-Trough CSL. This represents a high stand sequence tract where the water column was at its deepest. Sea level fall or sediment progradation forced a shallowing of the water column and a facies shift back to a beach environment forming the upper WG-Tabular CSL. This lithofacies therefore represents a forced regressive systems tract.

The latest stage of the regressive systems tract is represented by the two Terra Cotta lithofacies, the TC-SML and the TC-FDL, moving from a tidally effected estuarine to a mud flat or salt marsh environment.

The sharp and sometimes erosional contact, the Windy Gully Erosion Surface, was identified by the presence of Terra Cotta rip-up clasts in the directly overlying Basal Conlomerate of the New Mountain Sandstone. This therefore suggests an erosional period and therefore sufficient relative base level drop to either cease deposition in places or result in isolated erosion. The presence of desiccation cracks in places suggests subaerial exposure also. This therefore represents the upper sequence boundary between S1 and S2.

The sequence S1 consists of the Windy Gully Sandstone and Terra Cotta Siltstone Formations representing a relative sea level rise with lithofacies shifts depending on the water column depth and subsequent progradation to the point of forced regression (see figure 11.2). A relative sea level drop resulted in subaerial exposure, erosion and a subsequent systems boundary. The erosional period is represented by the Windy Gully Erosion Surface. The Windy Gully Erosion Surface was the result of only a small relative sea level drop as it was only seen to be erosional at one location (Handsley Valley) and showed subaerial exposure where observed elsewhere, seen by desiccation cracking.

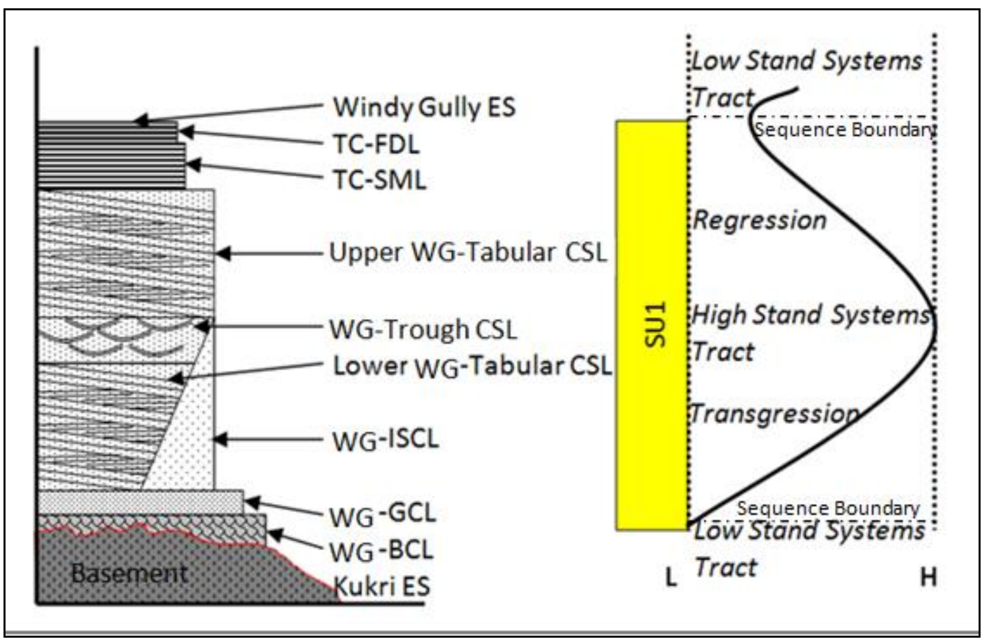

Figure 11.2 Schematic diagram of S1, the Windy Gully and Terra Cotta Siltstone Formations and sequence stratigraphy tract progression

11.3c Sequence Boundary - The Windy Gully Erosion Surface

The Windy Gully Erosion Surface was first suggested by Harrington (1965) and has been debated as to its regional significance. Observation in the field area has found the contact to be very sharp for the most part but lacking erosional properties. In one location however, Knobhead location (Handsley Valley), the Windy Gully Erosion Surface has been identified due to the presence of Terra Cotta Siltstone Formation rip-up clasts deposited directly above in the New Mountain Basal Conglomerate Lithofacies (NM-BCL). This surface can therefore be identified as both erosional and conformable in places, the result of a relative base (sea) level drop and the initiation of a low stand systems tract. The Windy Gully Erosion Surface is therefore the bounding unconformity or correlative conformity between the two sequences S1 (the Windy Gully Sandstone and Terra Cotta Siltstone Formations) and S2 (the New Mountain Sandstone Formation).

The Windy Gully Erosion Surface however was not as erosive as the other erosion surfaces observed and suggests only a slight drop in relative sea level resulting in localized erosion in places and subaerial exposure in others.

11.3d Sequence 2 (S2) - The New Mountain Sandstone Formation

The New Mountain Sandstone Formation (NMSst) is bound at its base and top by the Windy Gully and Heimdall Erosion Surfaces respectively, both erosional and conformable in places. The NMSst and the lithofacies within represent the rise in relative base (sea) level and the subsequent sedimentation following; and therefore the beginning of the second sequence (S2). The author suggests that the NMSst represents a transgressive to high stand to regressive systems tract similar to what is seen in the WGSst scenario but without an extensive basal erosion surface like the KES.

The NMSst is split into four lithofacies consisting of: the New Mountain Gully Basal Conglomerate Lithofacies (NM-BCL); Granular Cross Bedded Sandstone Lithofacies (NM-GCL); upper and lower Low Angle Tabular Cross Bedded Sandstone (NM-Tabular CSL); and the High Angle Trough Cross Bedded Sandstone (NM-Trough CSL)

The NM-BCL is a low angle tabular cross bedded feldsarenite with Terra Cotta like rip-up clasts, seen only at Knobhead (Handsley Valley). This represents deposition of eroded Terra Cotta Siltstone Formation within the tabular cross beds. The interpretation of the NM-BCL is of a shallow beach environment after the truncation of the Terra Cotta estuarine and mud flat/salt marsh environment and therefore the initiation of progradation and a transgressive systems tract.

The New Mountain Granule Cross Bedded Lithofacies (NM-GCL)is a very coarse sand to granule low angle cross bedded feldsarenite sandstone. This is also interpreted as an initial beach environment and represents the continuation of a coarse sandy beach environment with feldspathic content as a result of rejuvenation of the source rock. This lithofacies represents a continuation of a transgressive systems tract.

The New Mountain lower Low Angle Tabular Cross Bedded Sandstone Lithofacies (NM-Tabular CSL) is a series of low angle, tabular cross bedded well sorted, bioturbated (*Skolithos* and *Heimdallia*), fine to medium sand quartzarenites interpreted as a beach environments but with less feldspar and finer, more well sorted sand sediments. The continuous reworking and weathering out of feldspar results in almost pure quartz arenite sandstone. This lithofacies also represents continued deposition with sea level rise in a transgressive systems tract.

The New Mountain High Angle Trough Cross Bedded Sandstone Lithofacies (NM-Trough CSL), a series of higher angle trough cross bedded well sorted fine to medium subfeldsarenites, represents the transition into the near shore shallow marine environment within the channelized breaker zone (see fig x). This represents the deepest water column stage and therefore a high stand systems tract. Note that the NM-Trough CSL lies between the upper and lower NM-Tabular CSL.

The New Mountain upper Low Angle Tabular Cross Bedded Sandstone Lithofacies (NM-Tabular CSL) is physically similar to the lower NM-Tabular CSL and consists of a series of low angle tabular cross bedded well sorted, *Skolithos* bioturbated, fine to medium sand quartzarenites interpreted as a beach environments but with less feldspar and finer, more well sorted sand sediments. This represents either a forced shallowing of the water column from continued progradation with no sea level rise or a relative drop in sea level. This results in a transition back to a beach environment. This lithofacies therefore represents a regressive systems tract. Thin very fine sandstone drapes in the upper NM-Tabular CSL indicate a possible marginal transition to an estuarine environment, like the Terra Cotta Siltstone Formation, but such a unit is not seen anywhere in the field area. The Upper NM-Tabular CSL is truncated by the Heimdall Erosion Surface which is therefore the next sequence boundary.

In summary, the Windy Gully Erosion Surface represents the basal bounding unconformity or relative conformity of the stratigraphic unit, SU2. A continued rise in sea level after the Windy Gully Erosion Surface event resulted in continued progradation forming gradually fining and increasingly well sorted low angle beach environments, represented by the NM-BCL, GCL and the lower Tabular CSL. A maximum water depth resulted in channelization of the New Mountain Sediments in a shallow near shore marine environment, the NM-Trough CSL. A sustained sea level high enabled the water column to shallow due to the continued progradation of sediment. This progradation forced a regressive systems tract and reintroduced a low angle tabular cross bedded beach setting. This is also shown by the reintroduction and abundance of the trace fossils *Skolithos* and *Heimdallia.* Silt bed horizons in this lithofacies indicate a marginal association with low energy Terra Cotta like environments but strata in the area suggests that in this case the sediments do not progress into an estuarine environment but to a low angle beach berm before the truncation by the HES. If the estuarine environment did exist, it would therefore have been removed by the HES event.

NM-Tabular CSL was then truncated by the HES recording a significant drop in relative sea level forming the next sequence boundary and acting as the separation between SU2 and SU3 (the Altar Mountain Formation)..

The systems tract progression is shown in figure 11.3 alongside a schematic stratigraphic column of the New Mountain Sandstone Formation. In summary, the New Mountain Sandstone represents the second full stratigraphic sequence showing transgression and regression between the two erosion surfaces (see figure 11.3). The sedimentology shows a relative sea level rise and fall resulting in subsequent lithofacies shifts similar to those seen in the Windy Gully –Terra Cotta S1.

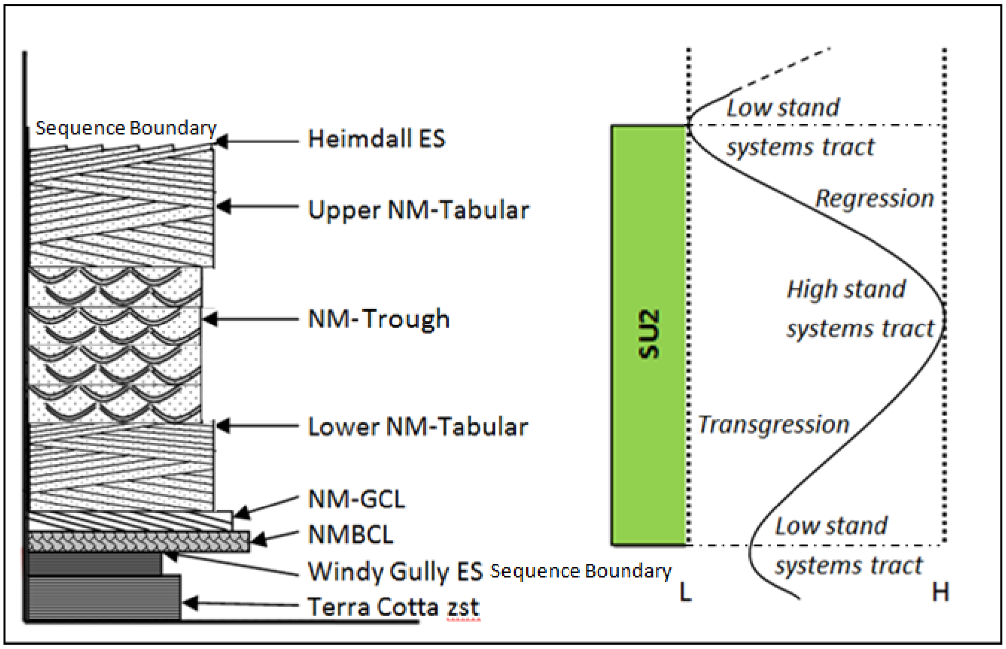

Figure 11.3 Schematic diagram of the New Mountain Sandstone Formation (S2) bound between two sequence boundaries (Windy Gully and Kukri ES) and sequence stratigraphy tract progression

11.3e Sequence Boundary - The Heimdall Erosion Surface

The Heimdall Erosion Surface (HES) represents a sequence boundary between SU2 (the New Mountain Sandstone Formation) and SU3 (the Altar Mountain Formation). The HES truncates the low angle tabular cross beds of the New Mountain Sandstone Formation representing an erosive period and therefore a sustained drop in base (sea) level. The HES truncation forms a saw tooth pattern in the cross bedded sandstones and is linked to the presence of biscuit shaped sandstone clasts. The saw tooth pattern combined with the sandstone biscuit shaped clasts indicates lithification of the sediment prior to erosion. At one location, in the Folkvanger Valley, the HES forms channels with thicker channel fill indicating a short lived transition into a fluvial setting. The HES suggests a large sea level fall due to substantial lithofacies, erosion down to lithified sediment, large range of exotic clasts and shift suggesting a substantial relative sea level drop.

11.3f Sequence 3 (S3) - The Altar Mountain Formation

The Altar Mountain Formation and its basal member, the Odin Arkose member (referred as the AM-BCL for consistency) comprise the next sequence, SU3.

The Altar Mountain Formation is split into 4 lithofacies: The AM-BCL is found at its base and directly overlies the HES, the sequence boundary from a sea level low stand. At one location (Folkvanger Valley) the AM-BCL suggests a fluvial setting due to east-west channelizing of the HES surface and AM-BCL channel fill. At all other locations the AM-BCL represent the earliest deposition and progradation forming an initially pebbly beach. This is the earliest stage of a transgressive systems tract due to a rise in relative sea level.

The AM-GCL is a tabular cross bedded medium to coarse sub- to feldsarenite interpreted as a coarse sandy beach environment. This represents continuation of deposition and a transgressive systems tract.

The AM-Tabular CSL is a low angled tabular cross bedded subfeldsarenite often interbedded with the AM-GCL. This is also interpreted as a low angled beach environment part of a transgressive systems tract. The interbedding of the AM-GCL and the AM-Tabular CSL suggests a continuous supply of fresh feldspathic sediment from the source and continued reworking weathers out the feldspar forming the AM-Tabular CSL.

The AM-Trough CSL, a trough cross bedded subfeld- to quartzarenite, is interpreted as near shore shallow marine and is the result of a deepening of the water depth and therefore channelizing in the surf to breaker zone/. This is therefore a high stand systems tract. The upper contact of the Altar Mountain Formation was not clearly seen so it can therefore only be speculated to have had a similar scenario to S1 and S2. All of the above combined produce a stratigraphic sequence moving from a low stand systems tract moving through transgression to a high stand (see figure 11.4). The author therefore speculates that it will follow a similar progression to what is seen in SU1 and SU 2 of the Windy Gully Sandstone, Terra Cotta Siltstone and New Mountain Sandstone Formations.

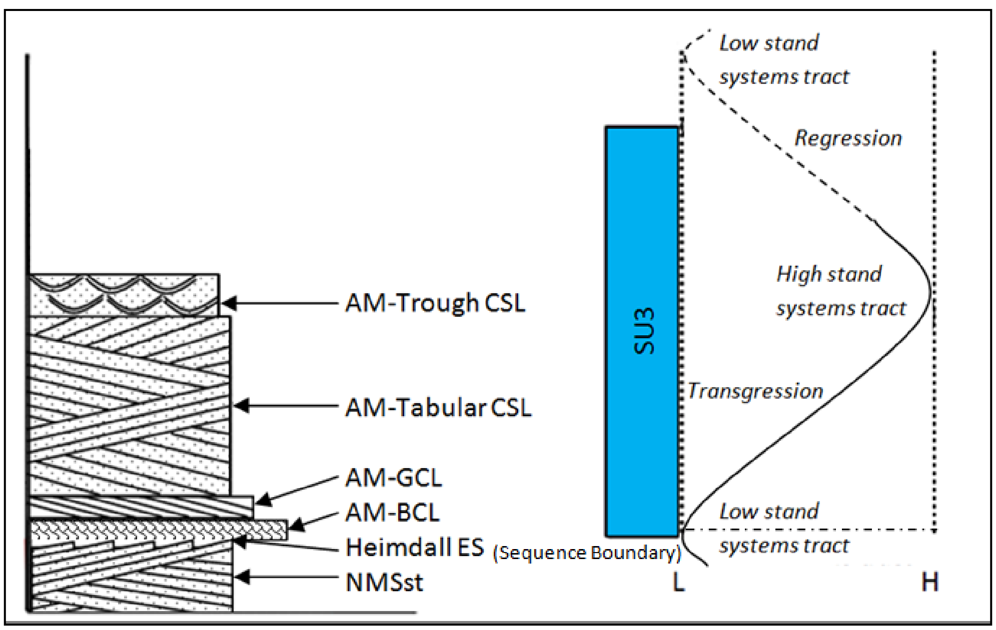

Figure 11.4 Schematic diagram of the Altar Mountain Sediments observed in the field and sequence stratigraphy progression throughout

11.4 Discussion and Interpretations

The two stratigraphic units (S1 and 2) represent two sequences between erosion surfaces and their relative conformities. They both progress from the basal erosion surface (or relative conformity and low stand systems tract); through lithofacies changes indicating an increasing water depth (transgression); to a high stand sequence tract (maximum water depth); to a forced shallowing scenario (due to sustained sea level high and continued progradation) or a relative sea level drop (regression); before being truncated by a another erosion surface (sequence boundary). The Altar Mountain formation was not fully measured and the upper contact not observed but the author speculates that decrease in feldspar content throughout and the lithofacies progression suggest a very similar scenario.

Combining the three stratigraphic units shows three sequences separated by sequence boundaries (see figure 11.5). The Altar Mountain line has been dotted as the sequence progression is speculated, but likely to be similar. The Windy Gully Sandstone and New Mountain Sandstone and Altar Mountain Formations are physically very similar in their cross bedded characteristic progression in the upper lithofacies, but differ towards their bases in terms of composition, degree of erosion at its basal contact and interaction with lower energy estuarine environments such as the TCzst or the WG-IZCL. This however just shows the degree in which the environments progressed and still shows a clear lithofacies progression.

The Windy Gully Sandstone is bound at its base by the Kukri Erosion Surface and has an extensive rubble horizon of granitic basal conglomerates (the WG-BCL). The New Mountain Sandstone formation however is bound at its base by a localized erosional event (the Windy Gully Erosion Surface) and has a thin scattered rip-up clast basal conglomerate of Terra Cotta Siltstone Formation that forms the NM-BCL horizon. The Windy Gully Erosion Surface is also subaerially uplifted, seen by desiccation cracking andin places only vary sharp and not erosional.

The Altar Mountain Formation is bound at its base by the HES sequence boundary and consists of both local and unidentified exotic clasts forming the AM-BCL. The conglomerates range in size angularity, roundness and progress from clast supported at the base to matrix supported moving into low angle cross bedded very coarse sand to granular sub- to feldsarenites. All three scenarios follow with low angled beach environments (apart from the AM-BCL at one location where a short lived fluvial setting is observed) and show a deepening in the water column into a shallow marine environment.

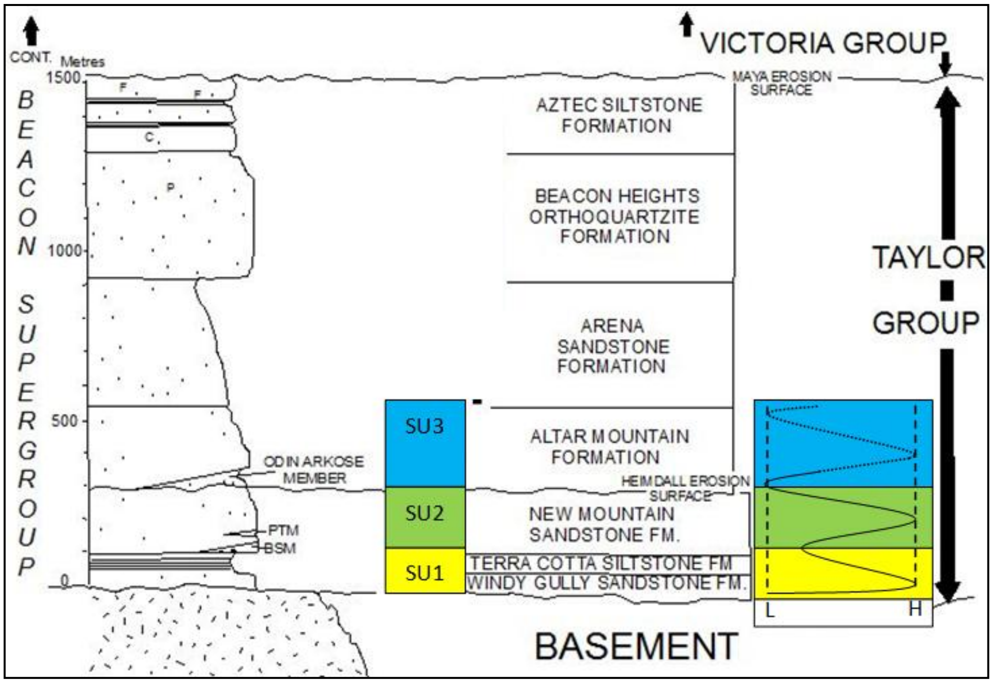

Figure 11.5 A schematic diagram of the sequence tract progression in cycles and speculated trend of the Altar Mountain Formation (S3)

The degree of erosion between the three sequence boundaries varies considerably in their lateral variation and depth of erosion. The Kukri Erosion surface is seen to be deeply weathered in all locations and suggests a sustained and significant sea level low. The Heimdall and Windy Gully Erosion surfaces however consist of both erosional and relatively conformable characteristics.

The Windy Gully Erosion Surface is seen as erosional at one location (the Handsley Valley) and is very sharp or has desiccation cracking (indicating subaerial exposure) elsewhere. In this case the Windy Gully Erosion Surface would have been a result of a slight drop in sea level and therefore resulting in a shallow erosion event.

The Heimdall Erosion Surface however varies from a significant truncation of lithified New Mountain Sandstone Formation cross beds to a mere influx of arkosic sediments. If the New Mountain Sandstone Formation progressed similarly to the Windy Gully Sandstone Formation then a Terra Cotta Siltstone equivalent would have been observed. This is not the case as no Terra Cotta equivalent is seen. This suggests that either a Terra Cotta equivalent was deposited and subsequently eroded away (along with New Mountain Formation sediments) or it was never deposited due to a facies shift from an early relative sea level drop.

The significant truncation of the New Mountain Sandstone Formation suggests a significant base level drop and therefore a probable uplift of the northern sediments as they show the highest degree of erosion. Uplift in the north could cause a significant relative sea level drop and facies shift in the north but not so much in the south (resulting in a small facies shift or just an influx of rejuvenated sediments.

Provenance analysis suggests local source from the Neoproterozoic Skelton Group and the DV2a Granite Harbour Intrusives, both local sources. The isolation of the Skelton Group source in the upper New Mountain Sandstone Formation sediments (seen by a lack of data signature for the Skelton Group and feldspar content in the upper NMSst) suggests insufficient base drop for sediment transport and only weathered source. The Skelton Group is situated north of the field area and therefore could have also been uplifted resulting in increased erosion and sufficient base drop to transport fresh feldspathic sediment to the lower Taylor sediments.

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Appendices

Appendix A: Field Data

Appendix A1: Stratigraphic Columns

The Following Stratigraphic columns have been removed due to amalgamation, lack of data or irrelevance to sediments of interest: 6, 7 & 13

Key to all Stratagraphic Columns

Lithologic

- Mudstone
- Siltstone
- Sandstone
- Matrix Supported Conglomerate
- Clast Supported Conglomerate
- Basement (Granite)

Contacts

- Sharp Planar
- Sharp Irregular
- Gradational Planar
- Gradational Irregular
- Sharp Erosional
- Gradational Erosional
- Rippled
- Obscured

Biologic

- Burrow vertical
- Burrow inclined
- Burrow Horizontal
- U shaped burrow
- Bioturbation

Sedimentary Structures

- Parallel Laminations
- Syneresis Cracks
- Dessication Cracks
- Channels

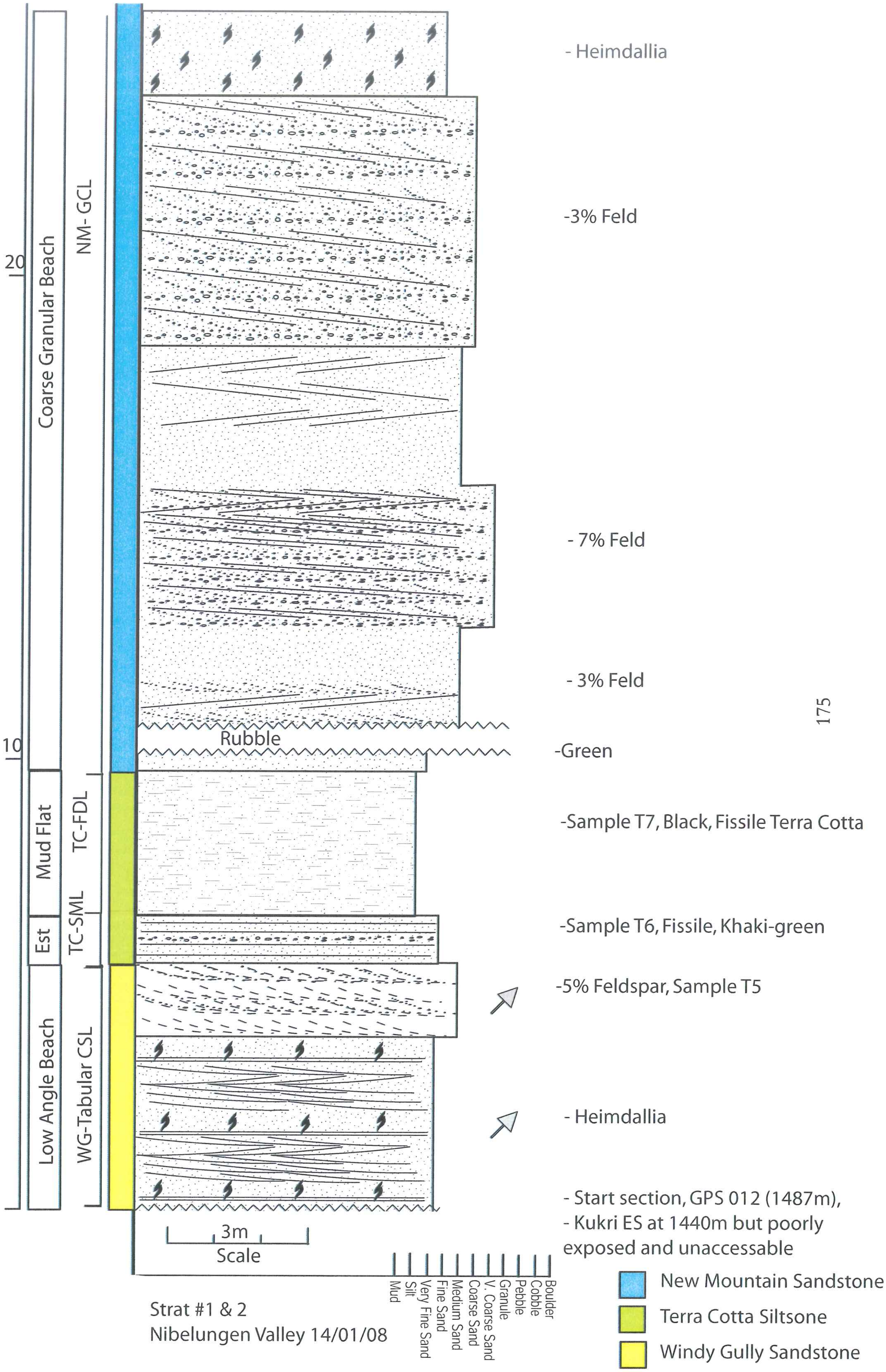
- Fining upwards
- Coarsening upwards
- Scattered granules
- Scattered pebble to boulder clasts
- Rip up clasts
- Concretions

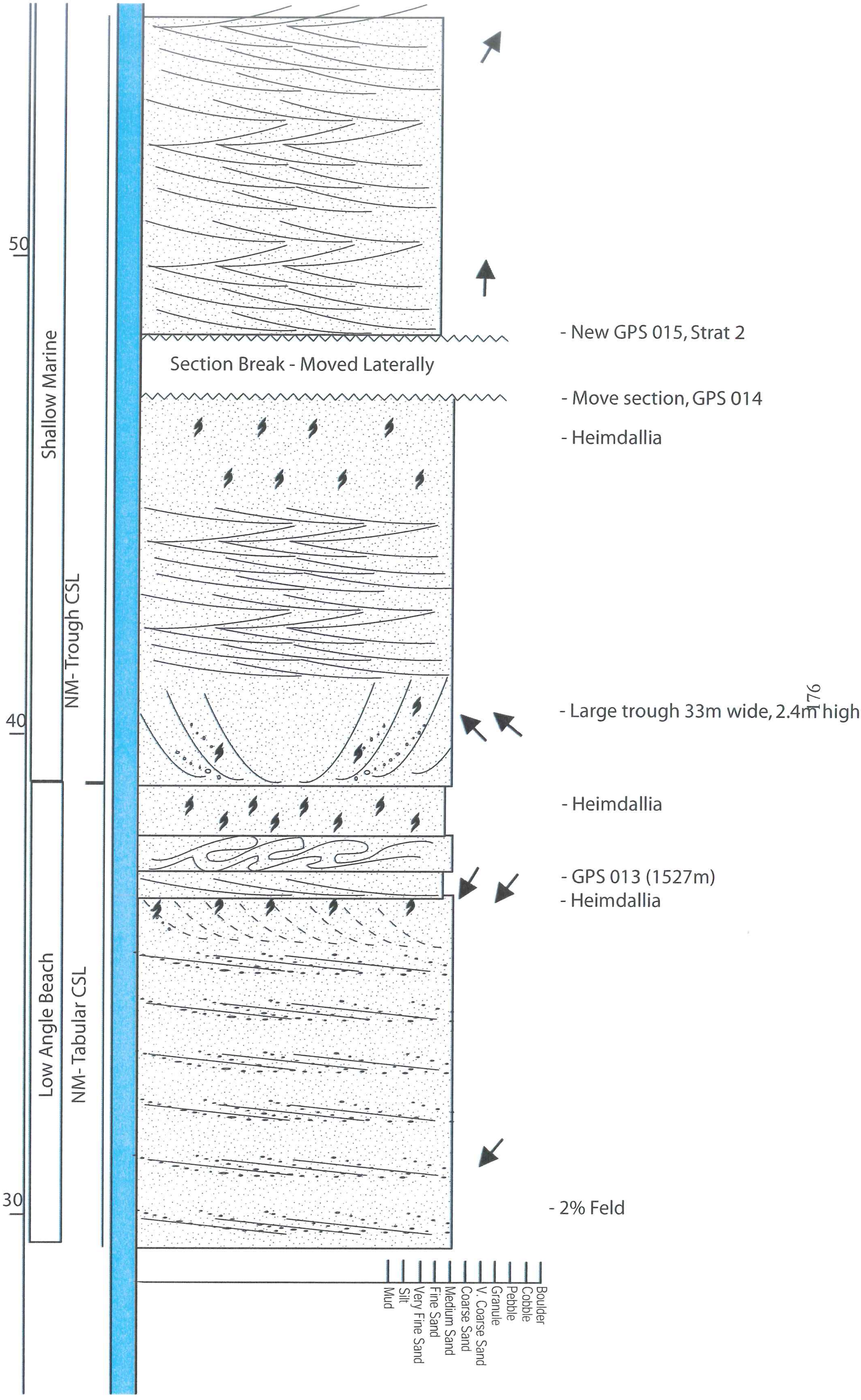
Cross Beds

- Trough
- Tabular
- Poor
- Mud Draped Forsets
- Granule Lined Forsets
- Granule to Pebble Lined Forsets
- Low angle X-beds

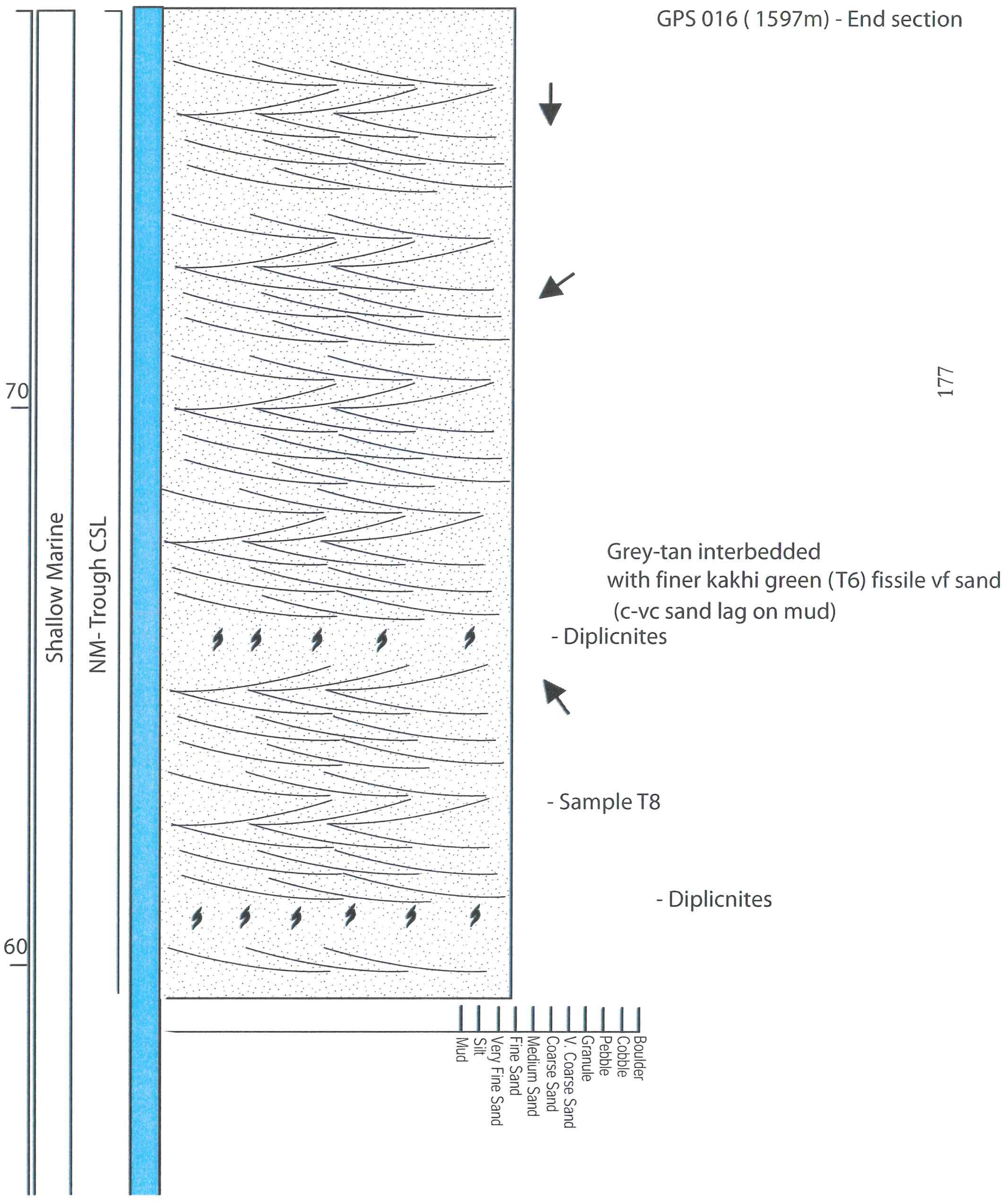
Other

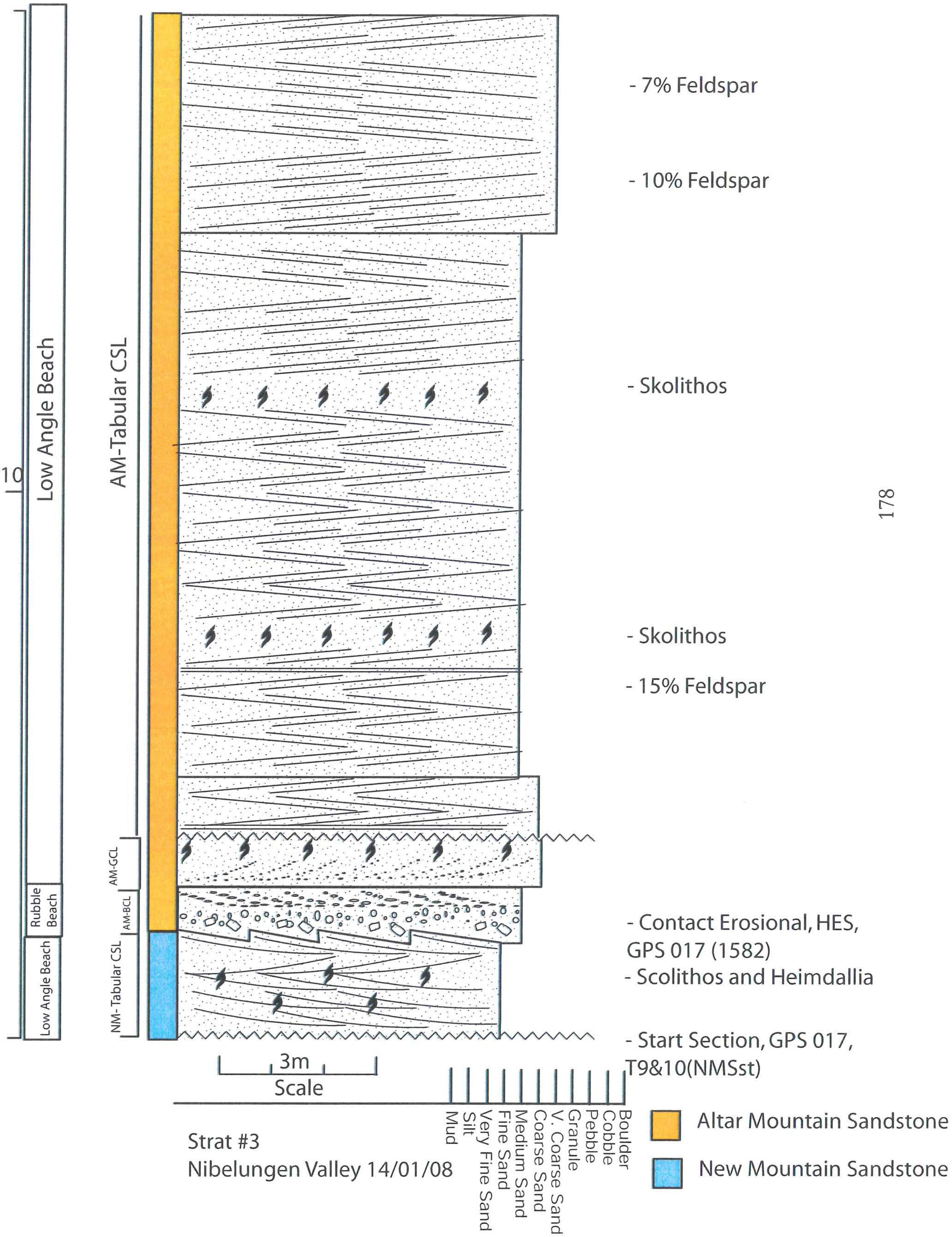
- Paleocurrent Direction (Measured)
- Paleocurrent Direction (Estimate)


20
10
Coarse Granular Beach
Mud Flat
Est
Low Angle Beach
NM- GCL
TC-FDL
TC-SML
WG-Tabular CSL
- Heimdallia
-3% Feld
- 7% Feld
- 3% Feld
Rubble
-Green
-Sample T7, Black, Fissile Terra Cotta
-Sample T6, Fissile, Khaki-green
-5% Feldspar, Sample T5
- Heimdallia
- Start section, GPS 012 (1487m),
- Kukri ES at 1440m but poorly exposed and unaccessable
3m
Scale
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder
Strat #1 & 2
Nibelungen Valley 14/01/08
New Mountain Sandstone
Terra Cotta Siltsone
Windy Gully Sandstone

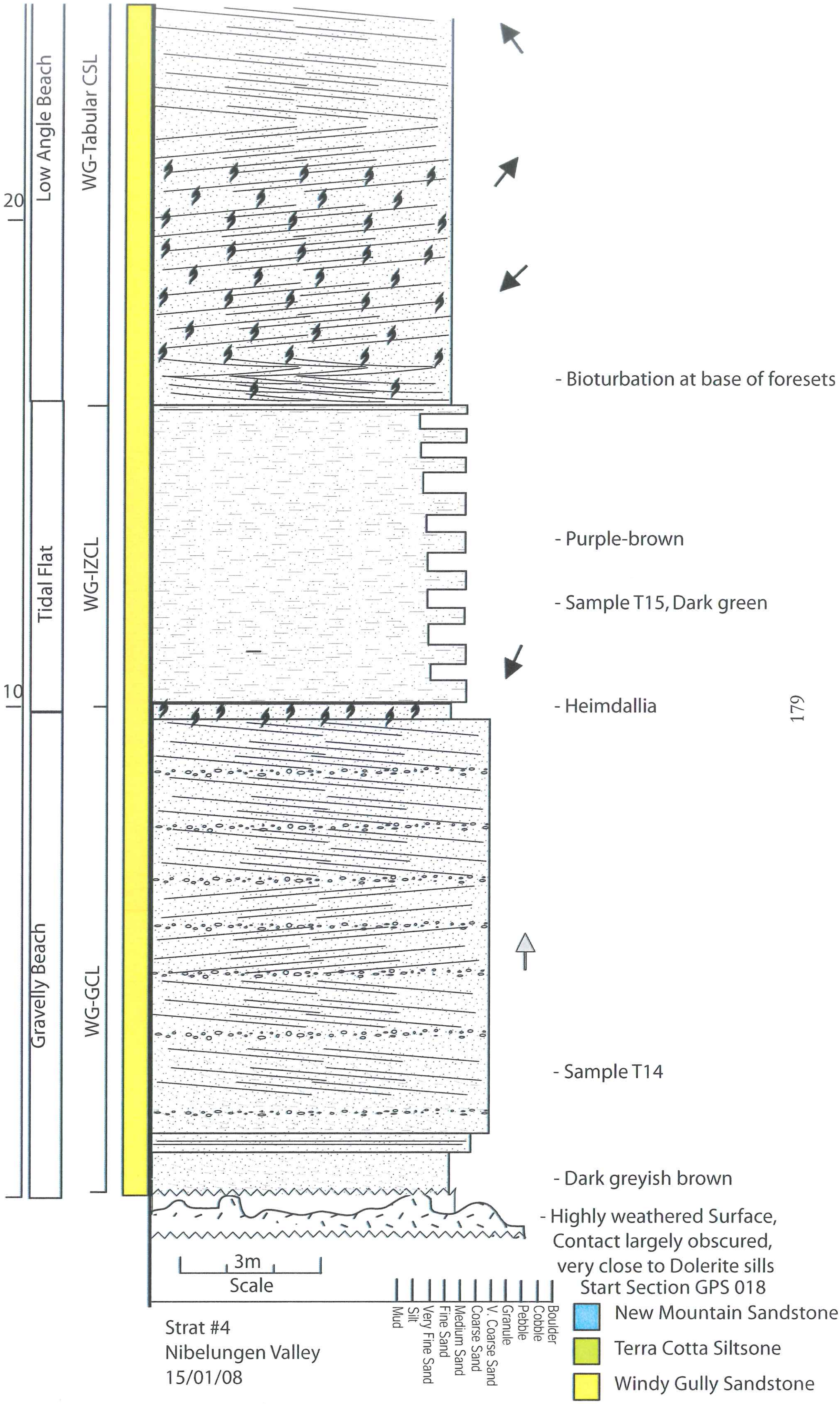


50
40
30
Shallow Marine
NM- Trough CSL
Low Angle Beach
NM- Tabular CSL
- New GPS 015, Strat 2
Section Break - Moved Laterally
- Move section, GPS 014
- Heimdallia
- Large trough 33m wide, 2.4m high
- Heimdallia
- GPS 013 (1527m)
- Heimdallia
- 2% Feld
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder

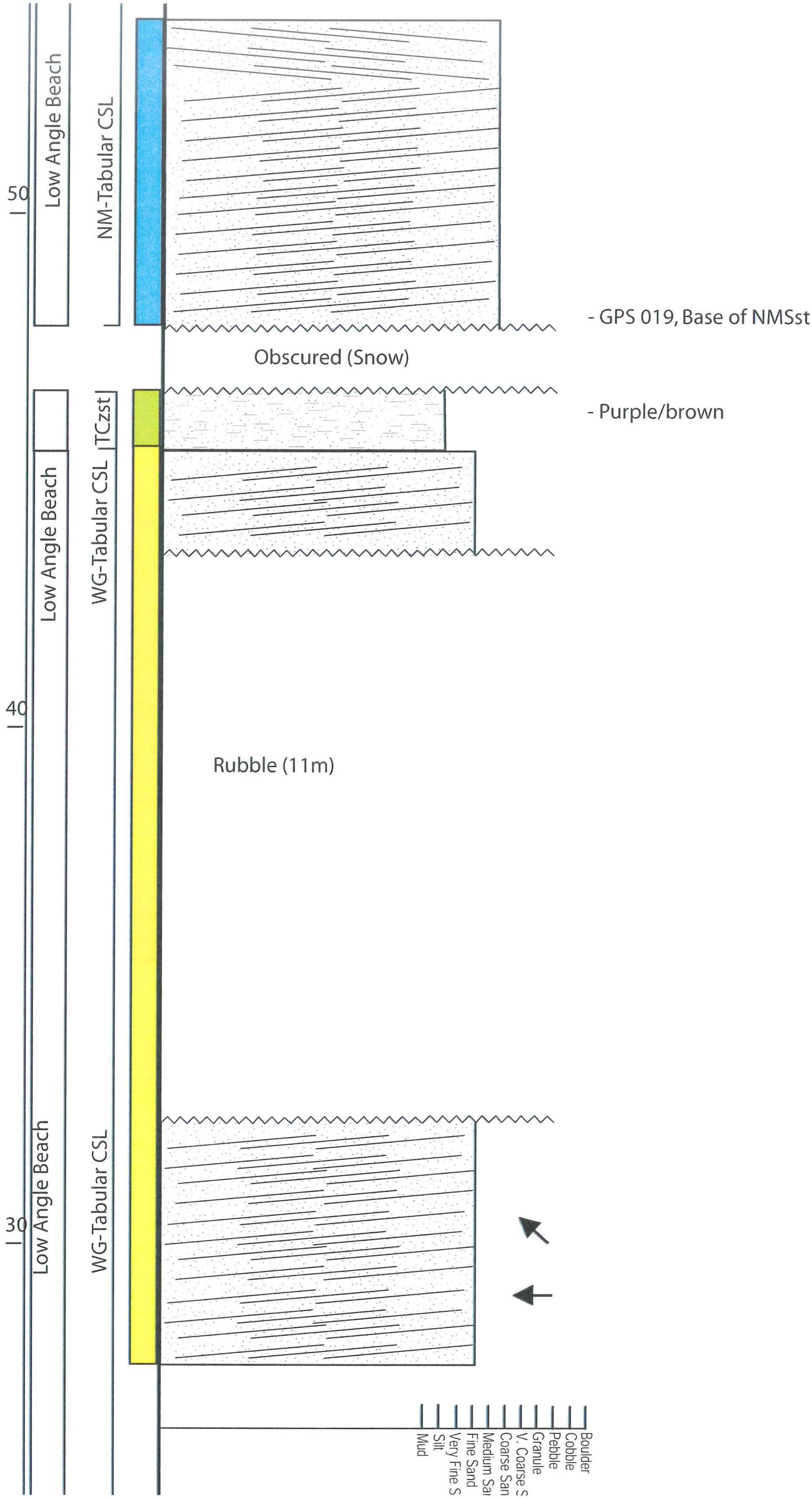

GPS 016 (1597m) - End section
Grey-tan interbedded
with finer kakhi green (T6) fissile vf sand
(c-vc sand lag on mud)
- Diplicnites
- Sample T8
- Diplicnites
70
60
Shallow Marine
NM- Trough CSL
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder



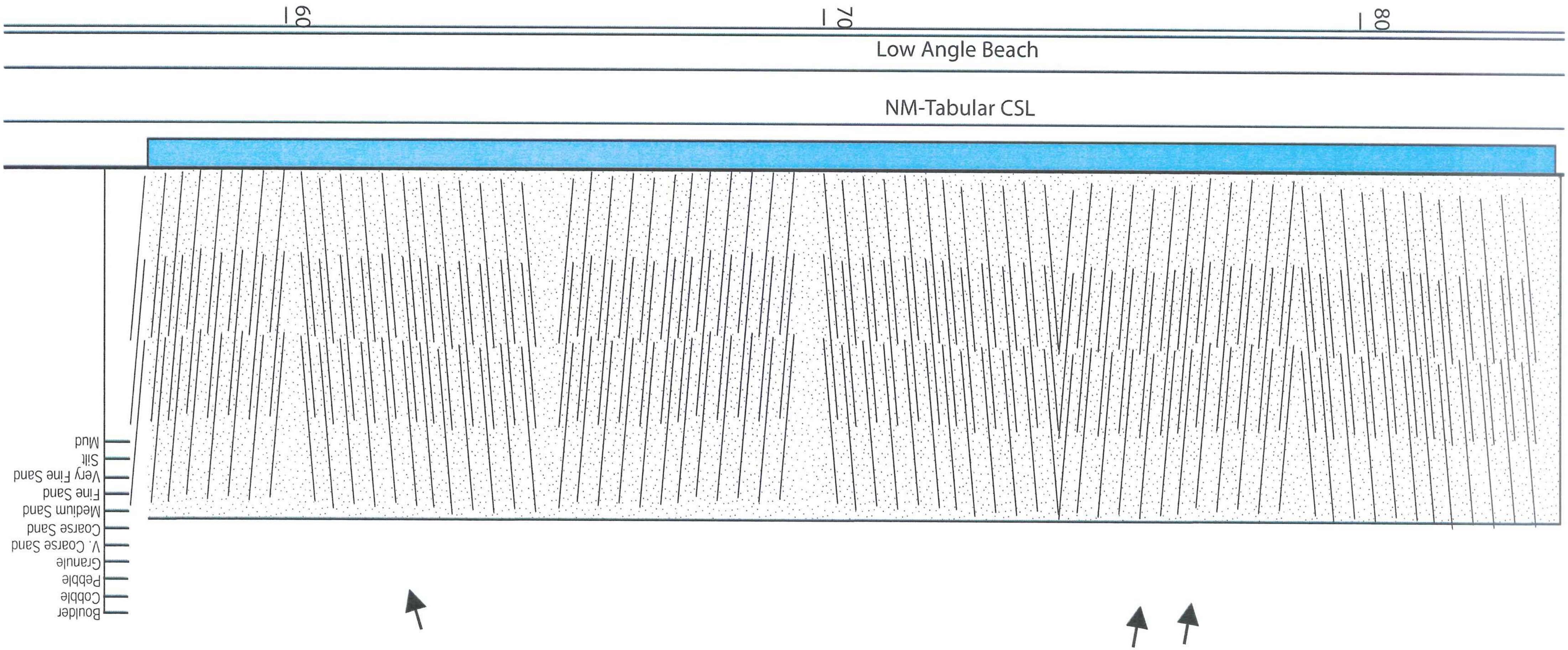
Strat #3
Nibelungen Valley 14/01/08



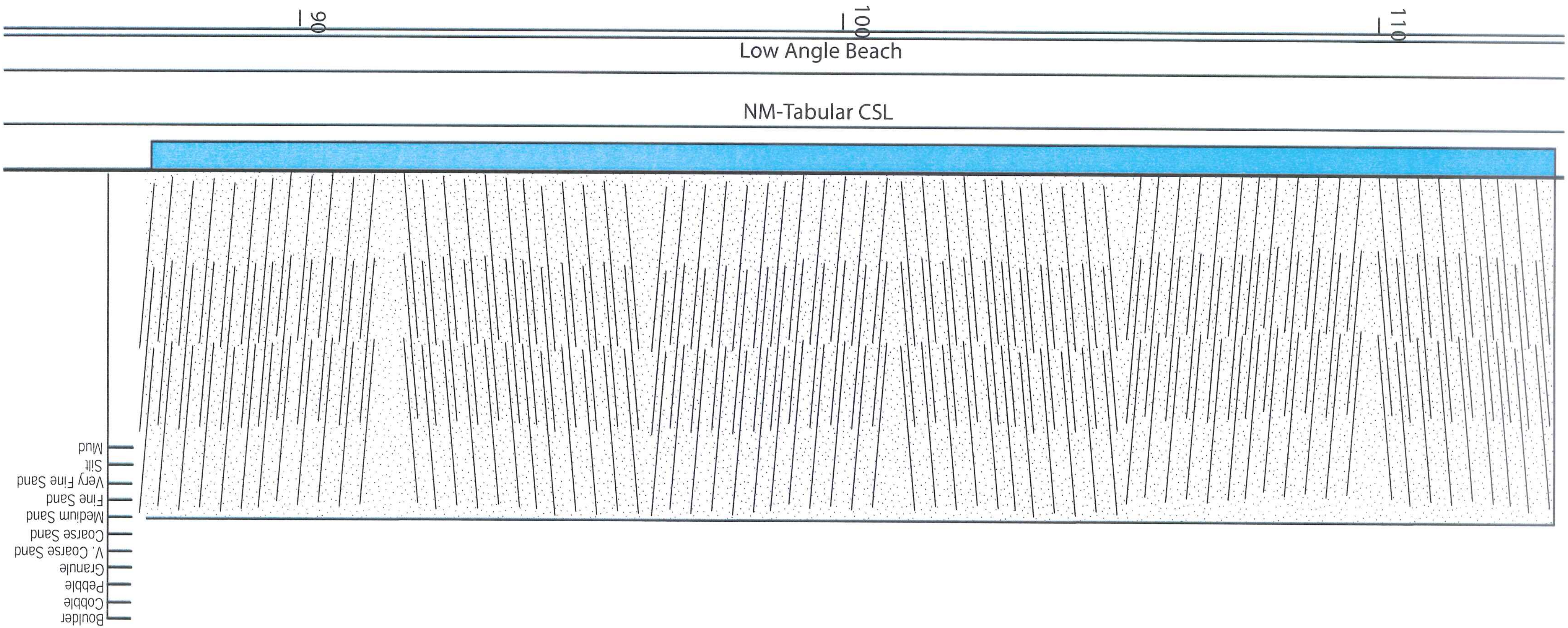
Low Angle Beach
Tidal Flat
Gravelly Beach
WG-Tabular CSL
WG-IZCL
WG-GCL
20
10
- Bioturbation at base of foresets
- Purple-brown
- Sample T15, Dark green
- Heimdallia
- Sample T14
- Dark greyish brown
- Highly weathered Surface, Contact largely obscured, very close to Dolerite sills
Start Section GPS 018
3m
Scale
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder
New Mountain Sandstone
Terra Cotta Siltsone
Windy Gully Sandstone
Strat #4
Nibelungen Valley
15/01/08

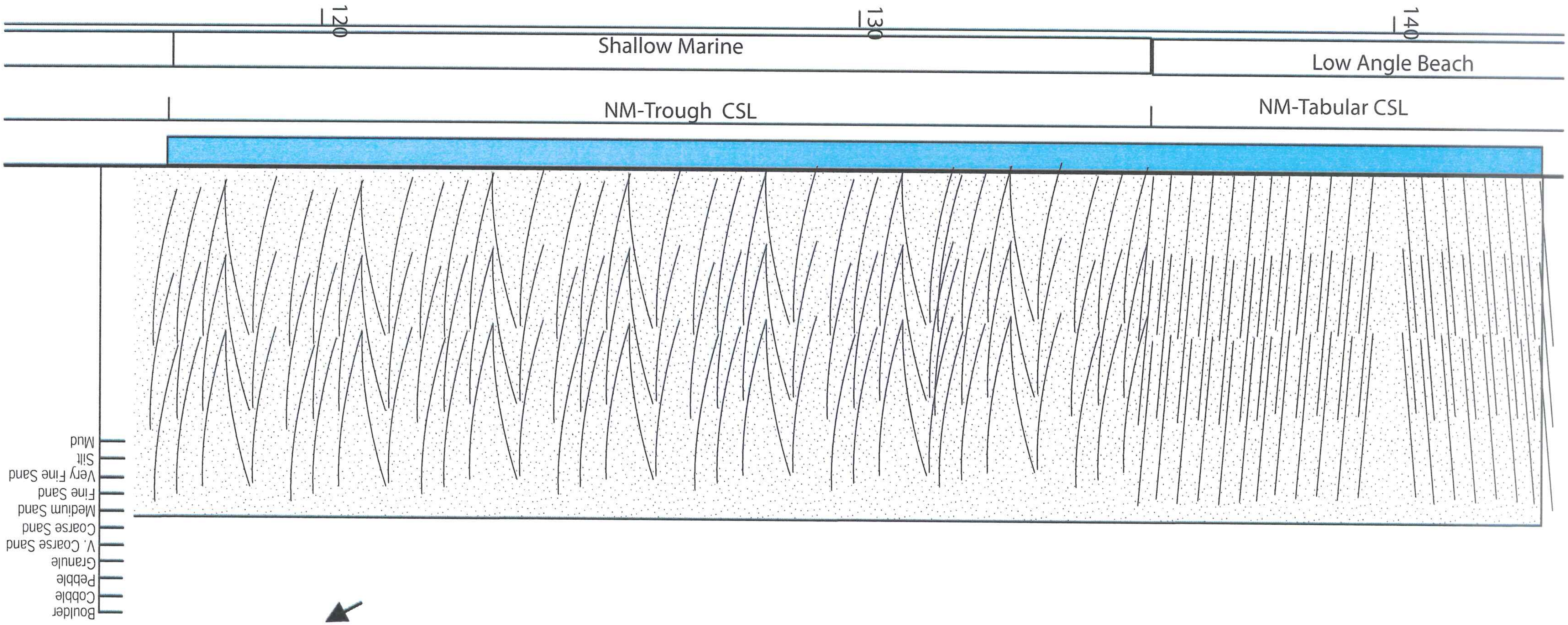


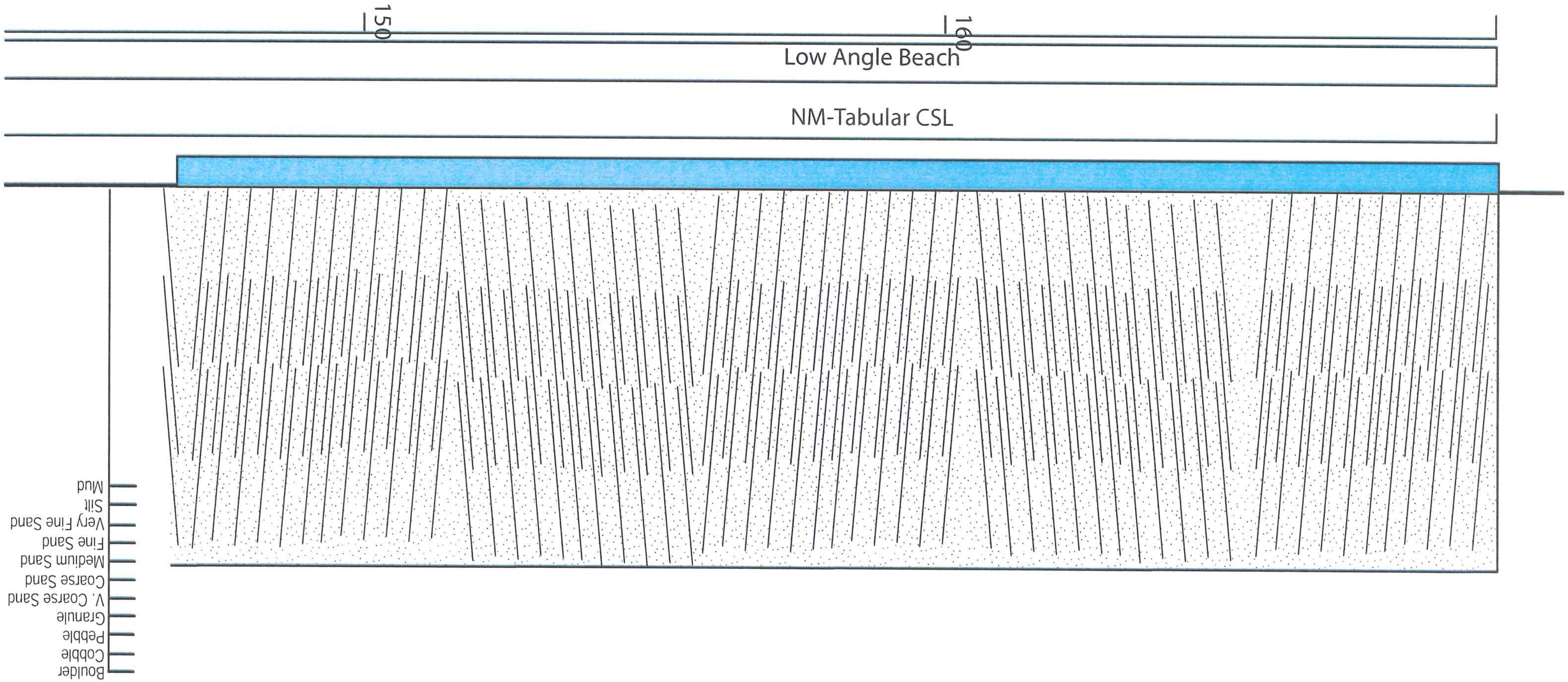
Low Angle Beach
NM-Tabular CSL
50
- GPS 019, Base of NMSst
Obscured (Snow)
- Purple/brown
TCzst
Low Angle Beach
WG-Tabular CSL
40
Rubble (11m)
Low Angle Beach
WG-Tabular CSL
30
Mud
Silt
Very Fine S
Fine Sand
Medium San
Coarse San
V. Coarse S
Granule
Pebble
Cobble
Boulder

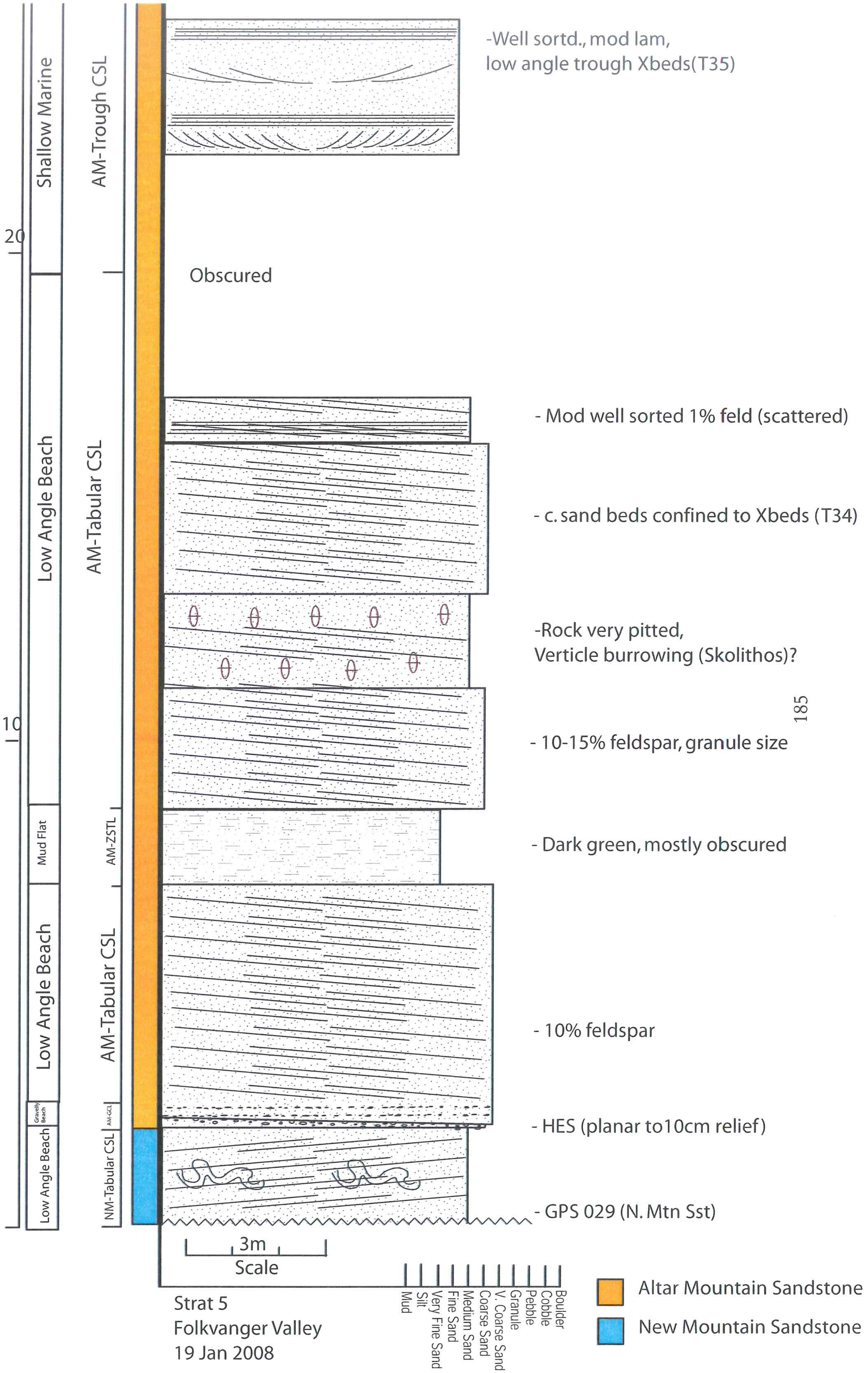


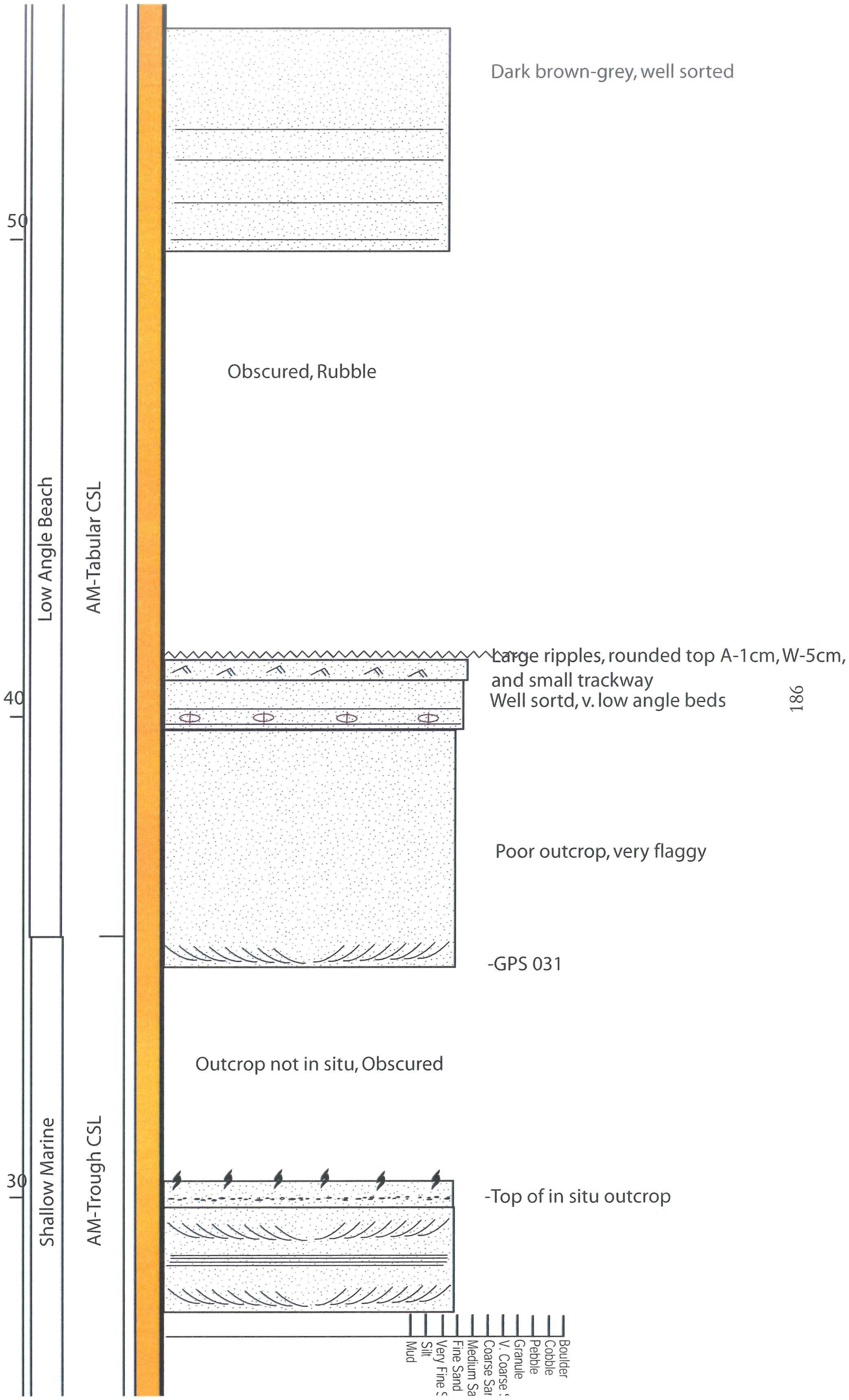
60
70
80
Low Angle Beach
NM-Tabular CSL
Boulder
Cobble
Pebble
Granule
V. Coarse Sand
Coarse Sand
Medium Sand
Fine Sand
Very Fine Sand
Silt
Mud

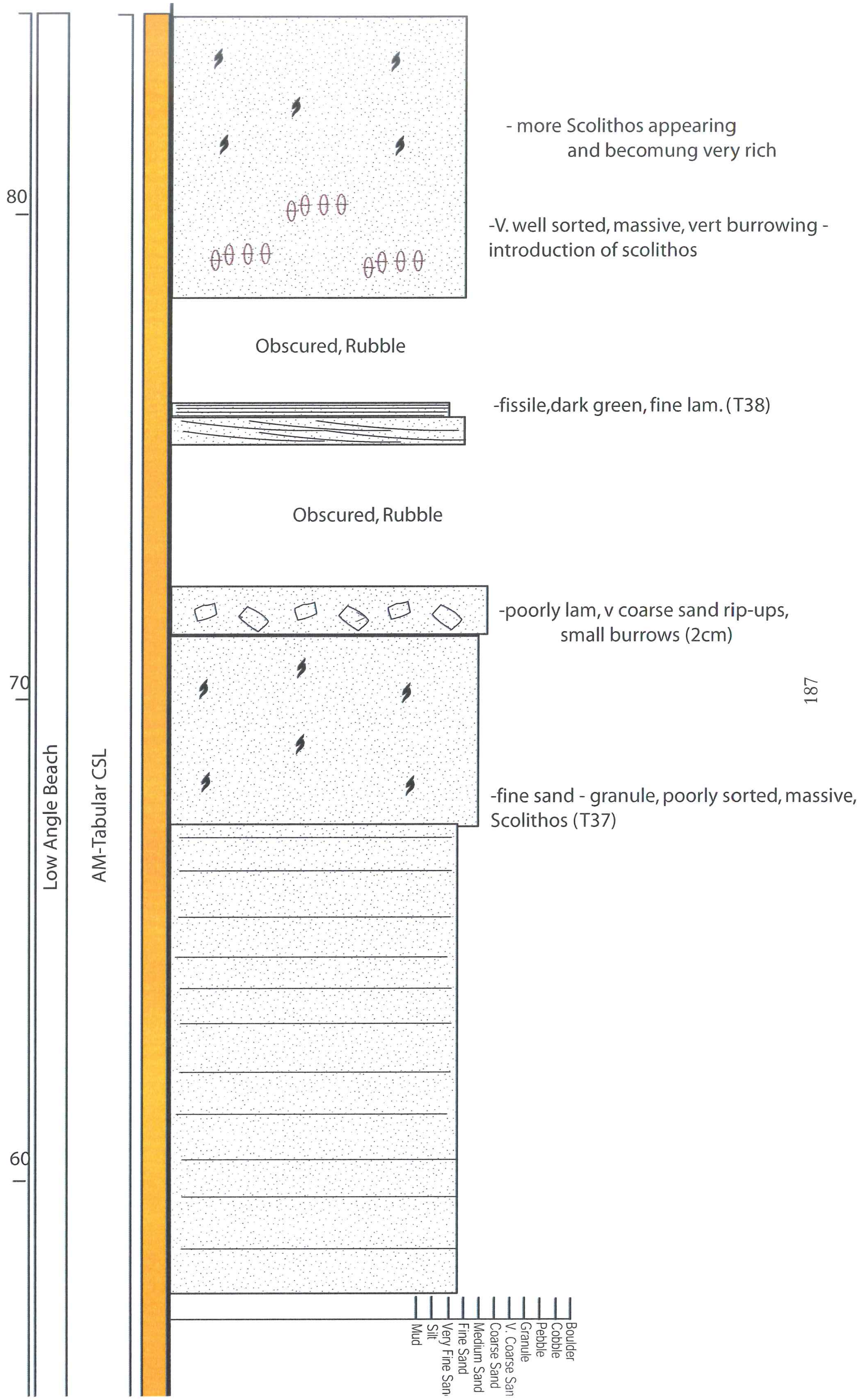

90
100
110
Low Angle Beach
NM-Tabular CSL
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder

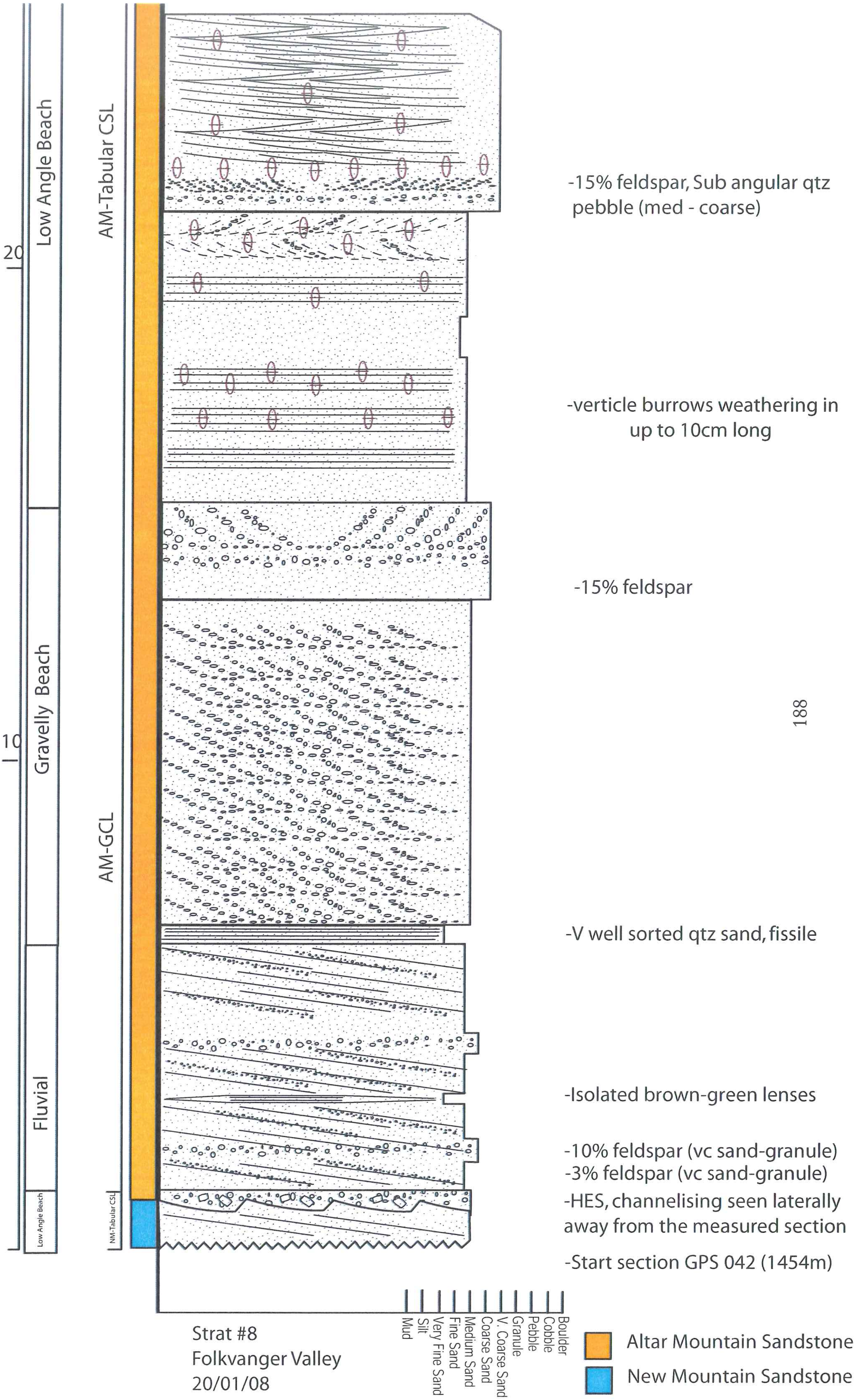

120
130
140
Shallow Marine
Low Angle Beach
NM-Trough CSL
NM-Tabular CSL
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder

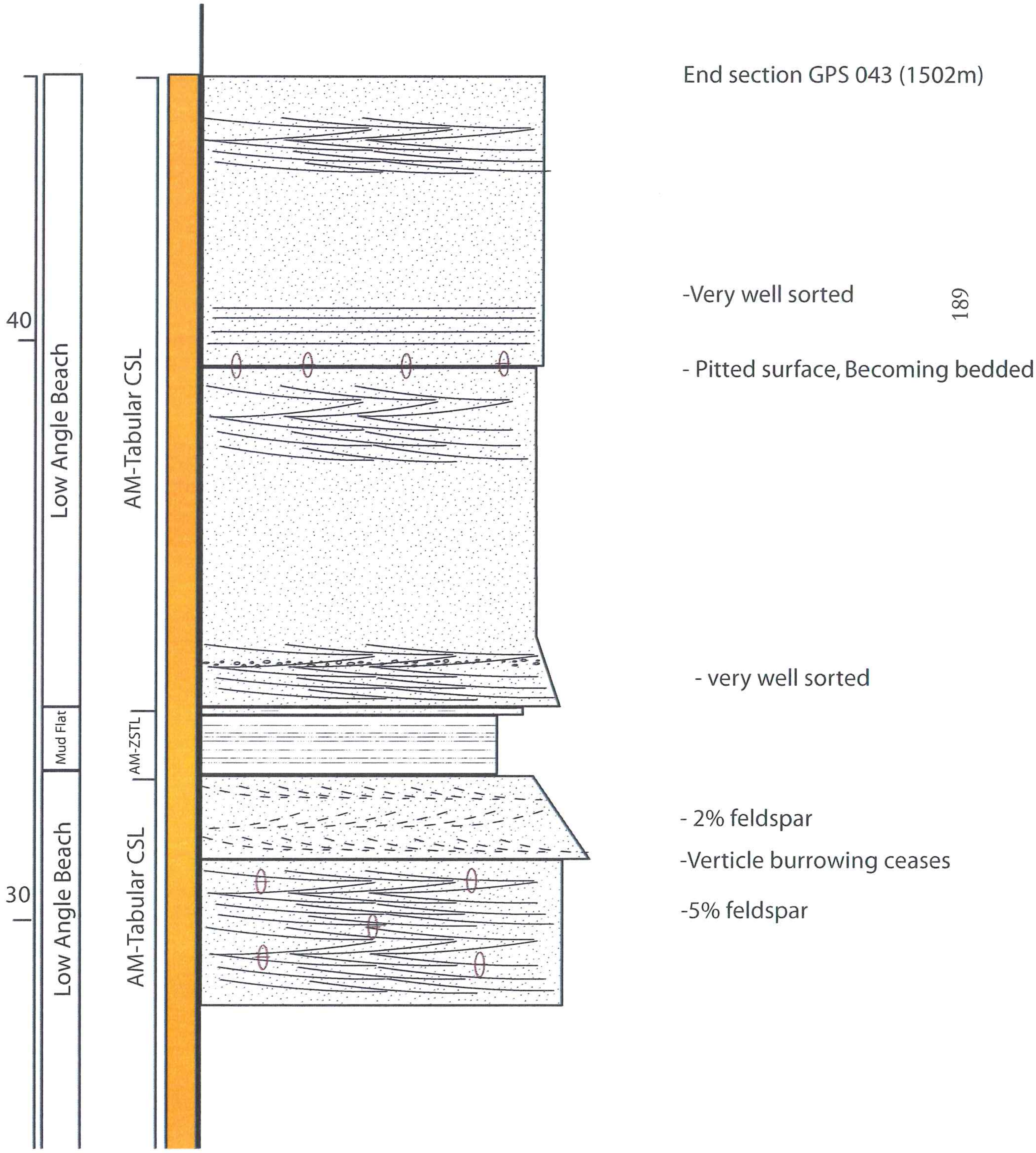

150
160
Low Angle Beach
NM-Tabular CSL
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder

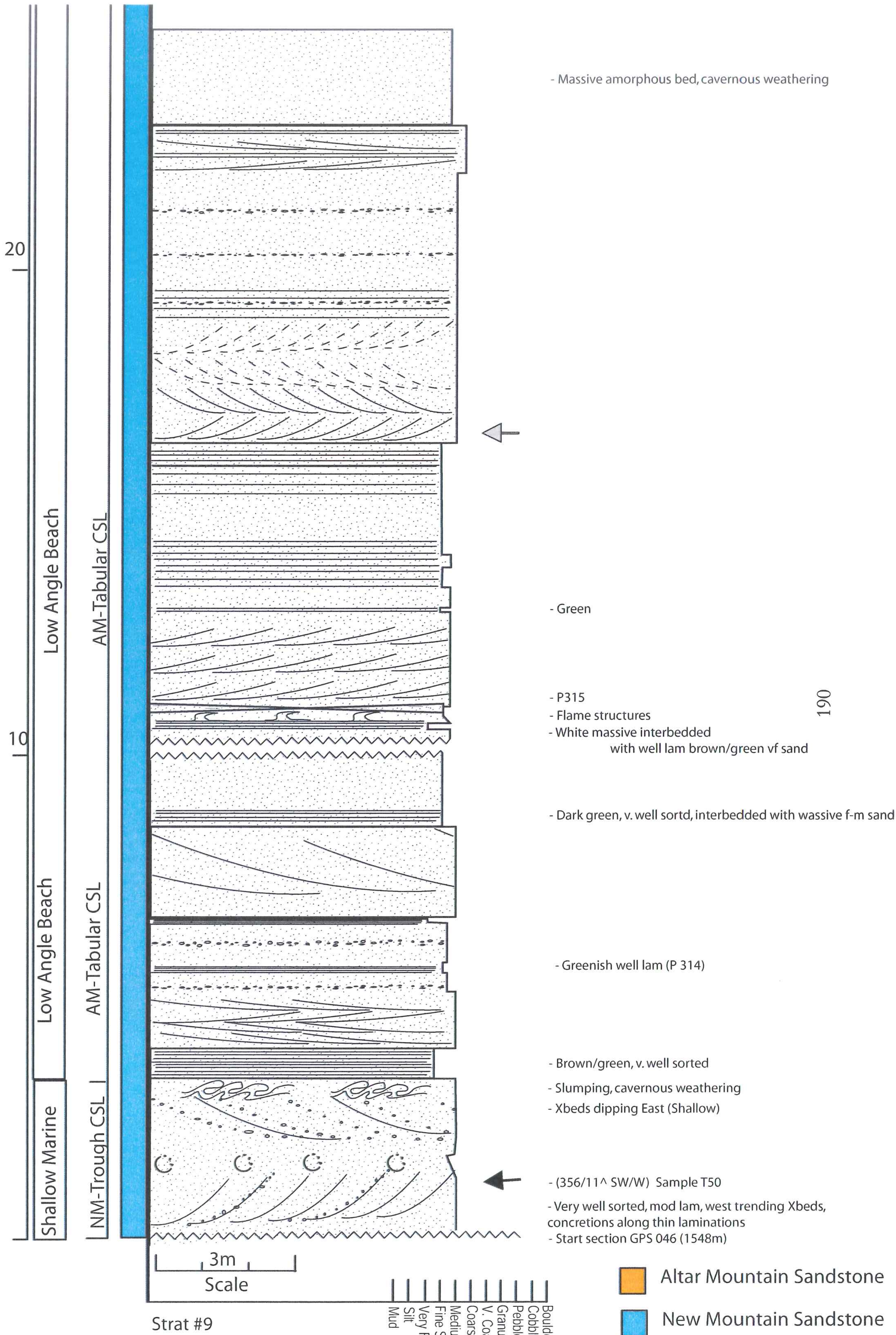

-Well sortd., mod lam,
low angle trough Xbeds(T35)
Obscured
- Mod well sorted 1% feld (scattered)
- c. sand beds confined to Xbeds (T34)
-Rock very pitted,
Verticle burrowing (Skolithos)?
- 10-15% feldspar, granule size
- Dark green, mostly obscured
- 10% feldspar
- HES (planar to10cm relief)
- GPS 029 (N. Mtn Sst)
Shallow Marine
AM-Trough CSL
20
Low Angle Beach
AM-Tabular CSL
10
Mud Flat
AM-ZSTL
Low Angle Beach
AM-Tabular CSL
Gravelly Beach
AM-GCL
Low Angle Beach
NM-Tabular CSL
3m
Scale
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder
Strat 5
Folkvanger Valley
19 Jan 2008
Altar Mountain Sandstone
New Mountain Sandstone


Dark brown-grey, well sorted
50
Obscured, Rubble
Low Angle Beach
AM-Tabular CSL
Large ripples, rounded top A-1cm, W-5cm,
and small trackway
Well sortd, v. low angle beds
40
Poor outcrop, very flaggy
-GPS 031
Outcrop not in situ, Obscured
Shallow Marine
AM-Trough CSL
30
-Top of in situ outcrop
Mud
Silt
Very Fine S
Fine Sand
Medium Sa
Coarse Sa
V. Coarse S
Granule
Pebble
Cobble
Boulder

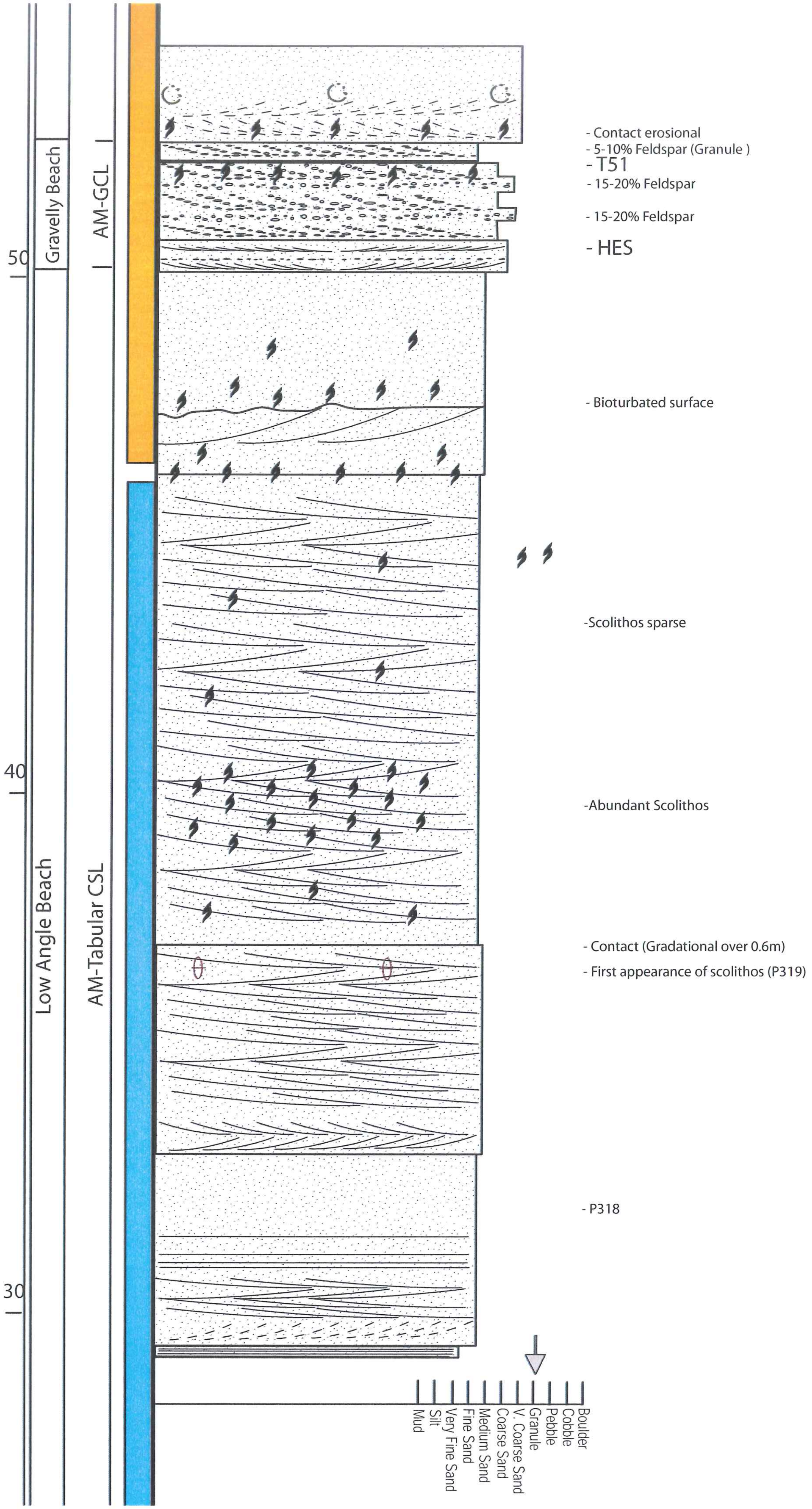

- more Scolithos appearing
and becomung very rich
80
-V. well sorted, massive, vert burrowing -
introduction of scolithos
Obscured, Rubble
-fissile,dark green, fine lam. (T38)
Obscured, Rubble
-poorly lam, v coarse sand rip-ups,
small burrows (2cm)
70
-fine sand - granule, poorly sorted, massive,
Scolithos (T37)
Low Angle Beach
AM-Tabular CSL
60
Mud
Silt
Very Fine San
Fine Sand
Medium Sand
Coarse Sand
V. Coarse San
Granule
Pebble
Cobble
Boulder

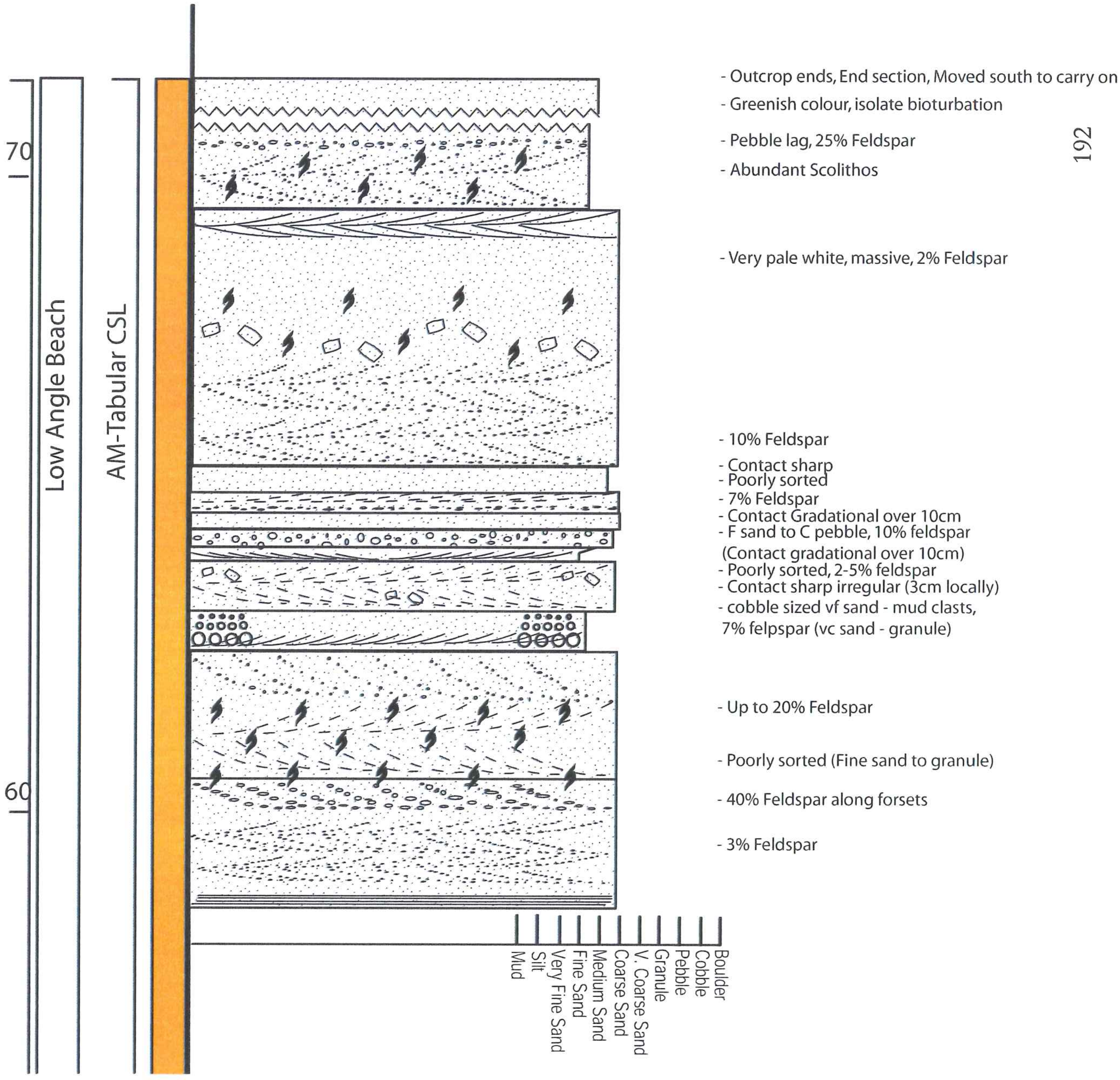

Low Angle Beach
Gravelly Beach
Fluvial
Low Angle Beach
20
10
AM-Tabular CSL
AM-GCL
NM-Tabular CSL
-15% feldspar, Sub angular qtz pebble (med - coarse)
-verticle burrows weathering in up to 10cm long
-15% feldspar
-V well sorted qtz sand, fissile
-Isolated brown-green lenses
-10% feldspar (vc sand-granule)
-3% feldspar (vc sand-granule)
-HES, channelising seen laterally away from the measured section
-Start section GPS 042 (1454m)
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder
Strat #8
Folkvanger Valley
20/01/08
Altar Mountain Sandstone
New Mountain Sandstone

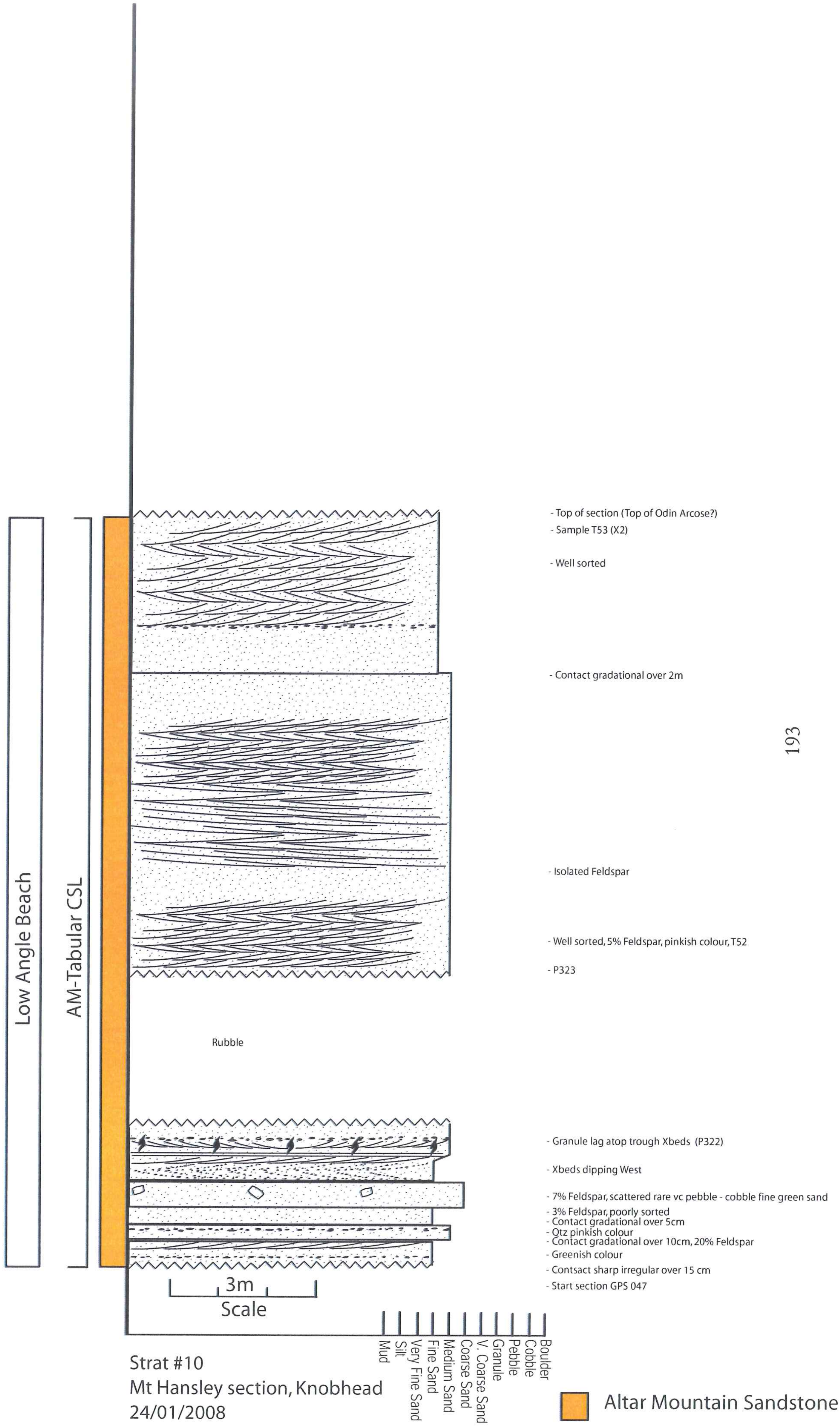

40
30
Low Angle Beach
Mud Flat
Low Angle Beach
AM-Tabular CSL
AM-ZSTL
AM-Tabular CSL
End section GPS 043 (1502m)
-Very well sorted
- Pitted surface, Becoming bedded
- very well sorted
- 2% feldspar
-Verticle burrowing ceases
-5% feldspar



Strat #9
Mt Hansley section, Knobhead
24/01/2008

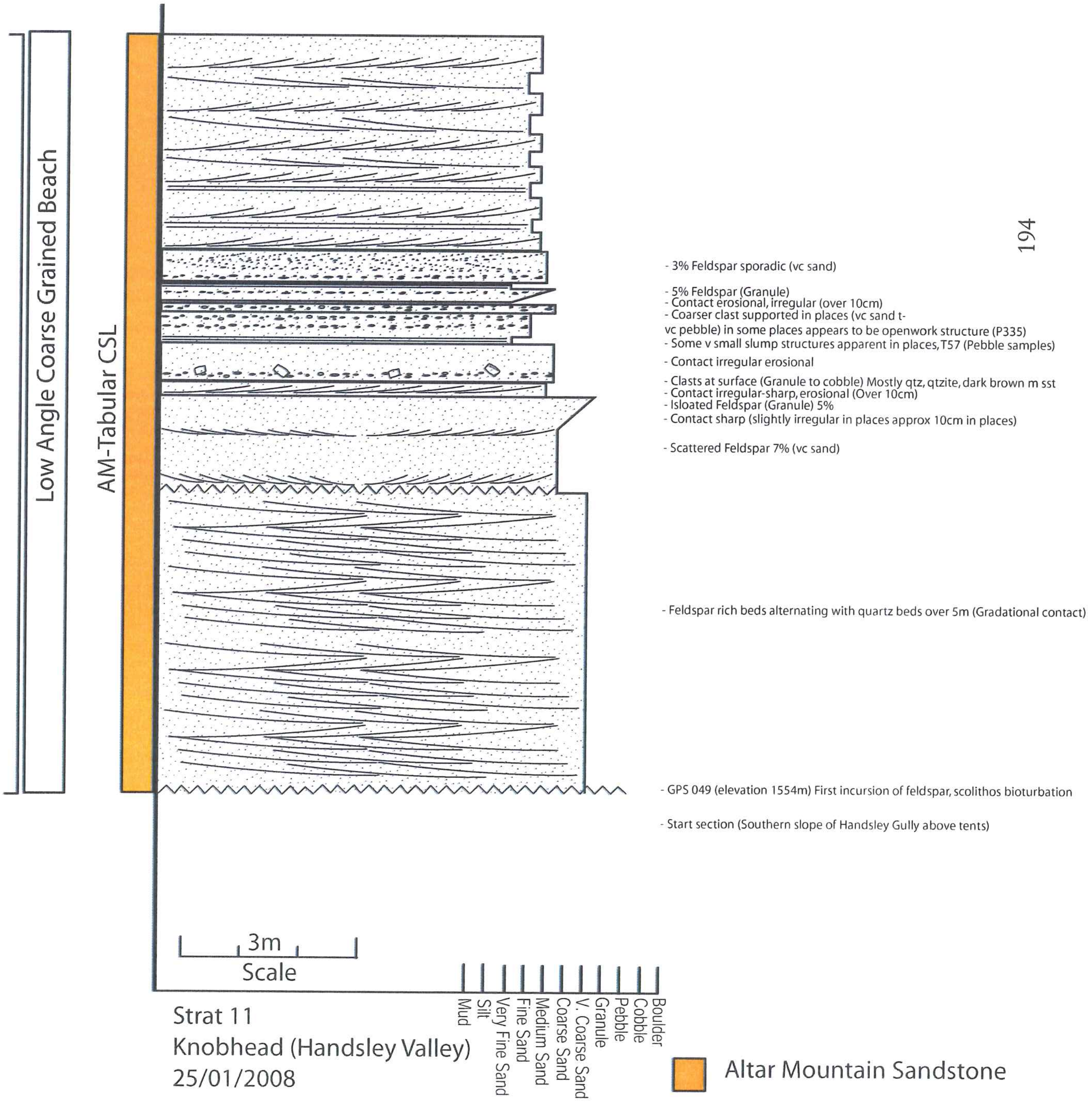

- Contact erosional
- 5-10% Feldspar (Granule)
- T51
- 15-20% Feldspar
- 15-20% Feldspar
- HES
- Bioturbated surface
-Scolithos sparse
-Abundant Scolithos
- Contact (Gradational over 0.6m)
- First appearance of scolithos (P319)
- P318
50
40
30
Gravelly Beach
Low Angle Beach
AM-GCL
AM-Tabular CSL
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder

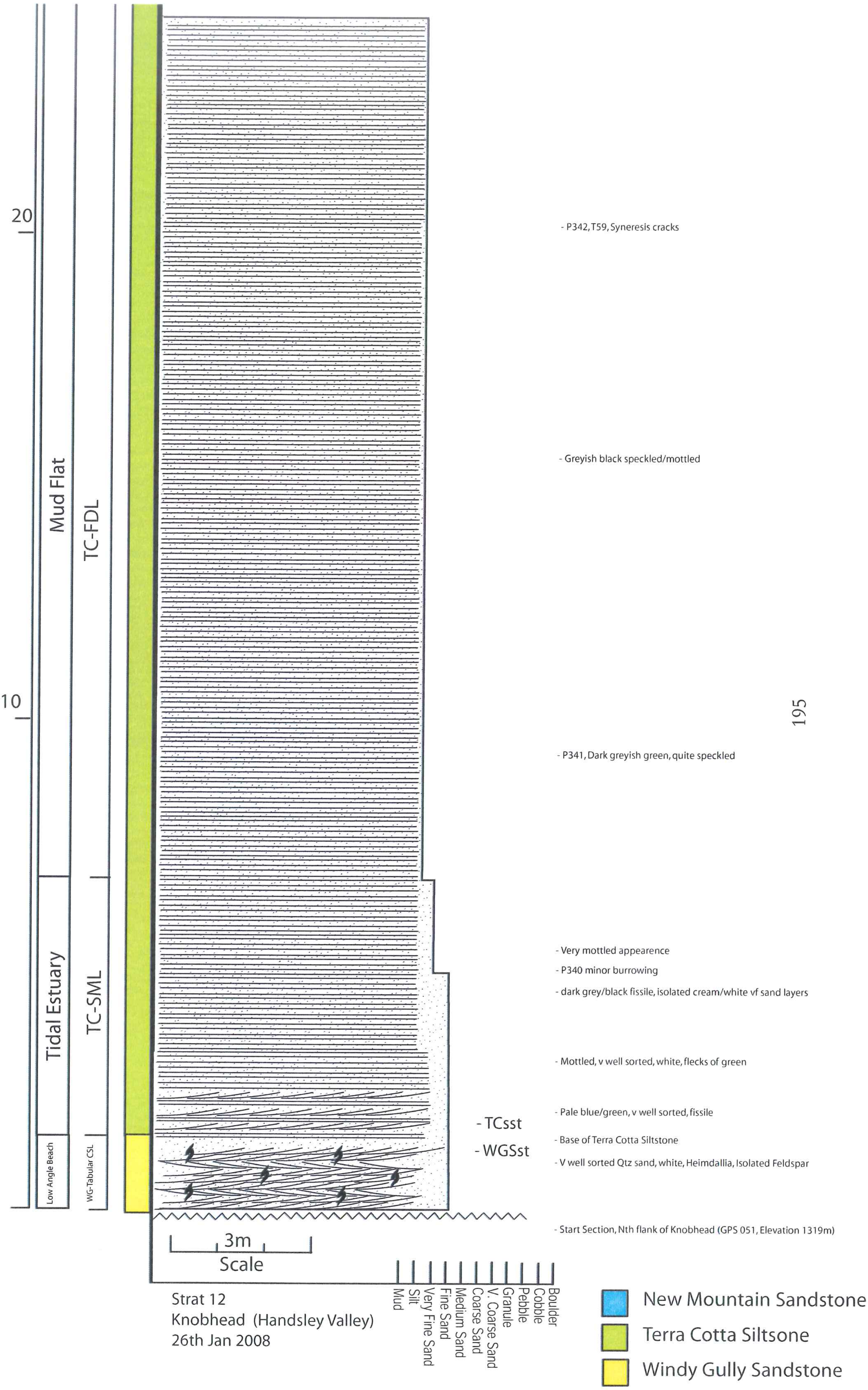

70
60
Low Angle Beach
AM-Tabular CSL
- Outcrop ends, End section, Moved south to carry on
- Greenish colour, isolate bioturbation
- Pebble lag, 25% Feldspar
- Abundant Scolithos
- Very pale white, massive, 2% Feldspar
- 10% Feldspar
- Contact sharp
- Poorly sorted
- 7% Feldspar
- Contact Gradational over 10cm
- F sand to C pebble, 10% feldspar
(Contact gradational over 10cm)
- Poorly sorted, 2-5% feldspar
- Contact sharp irregular (3cm locally)
- cobble sized vf sand - mud clasts,
7% felpspar (vc sand - granule)
- Up to 20% Feldspar
- Poorly sorted (Fine sand to granule)
- 40% Feldspar along forsets
- 3% Feldspar
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder

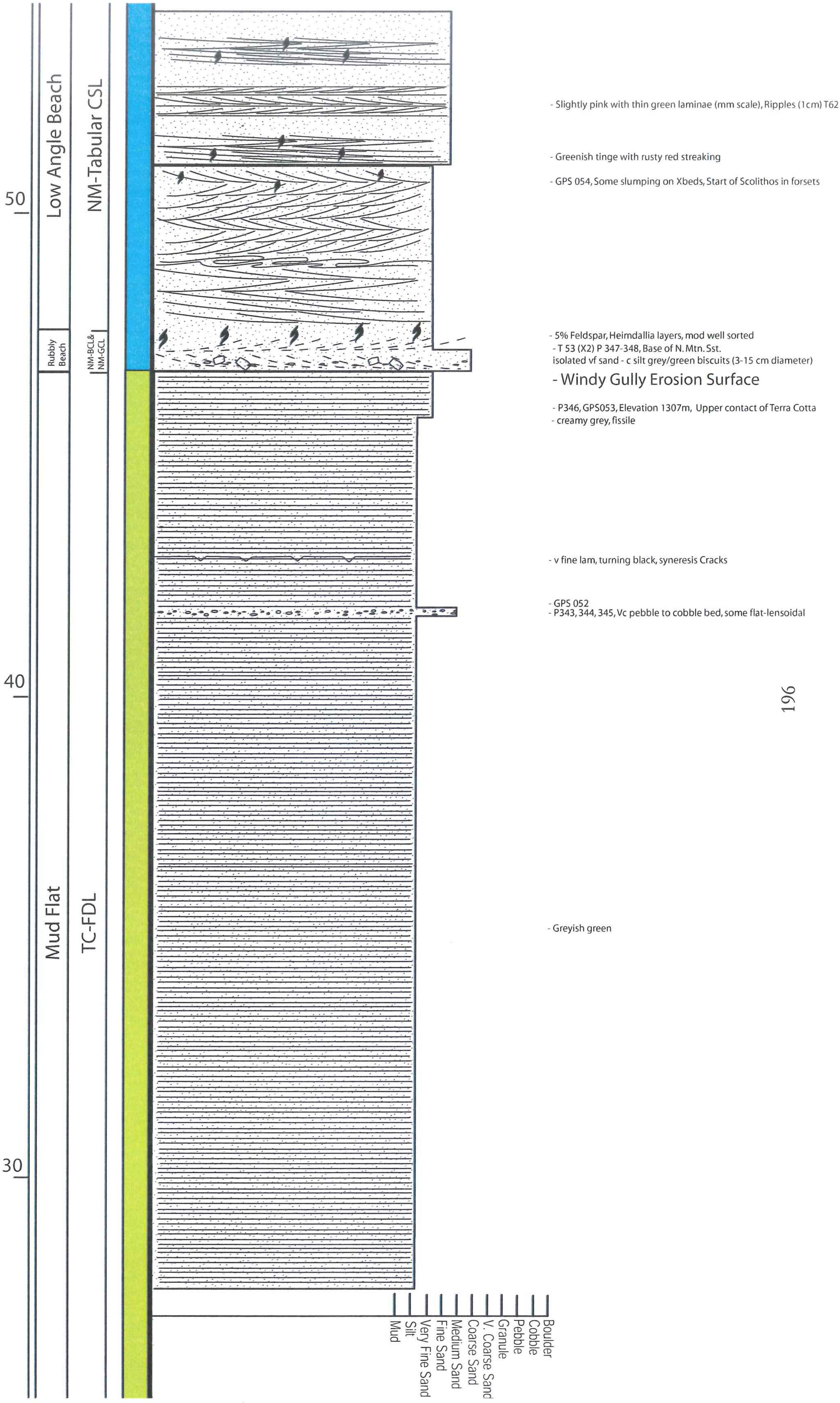


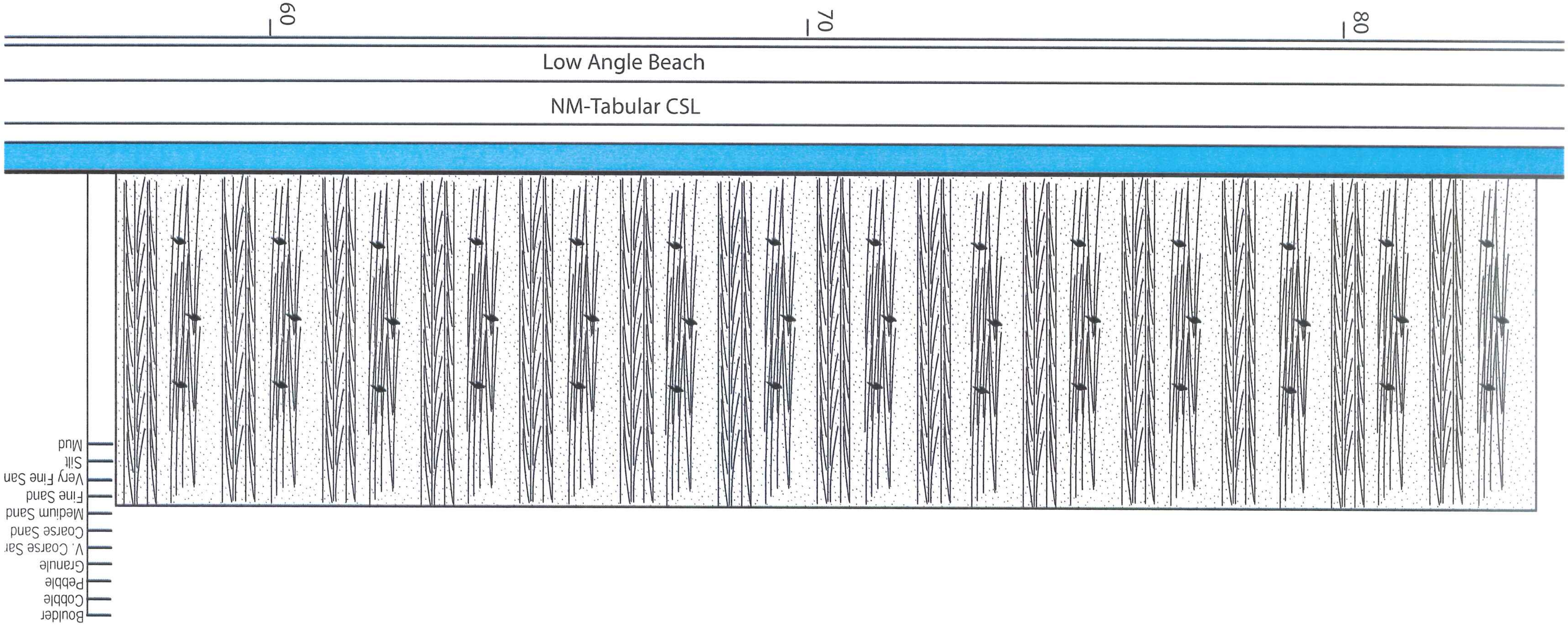
Strat #10
Mt Hansley section, Knobhead
24/01/2008

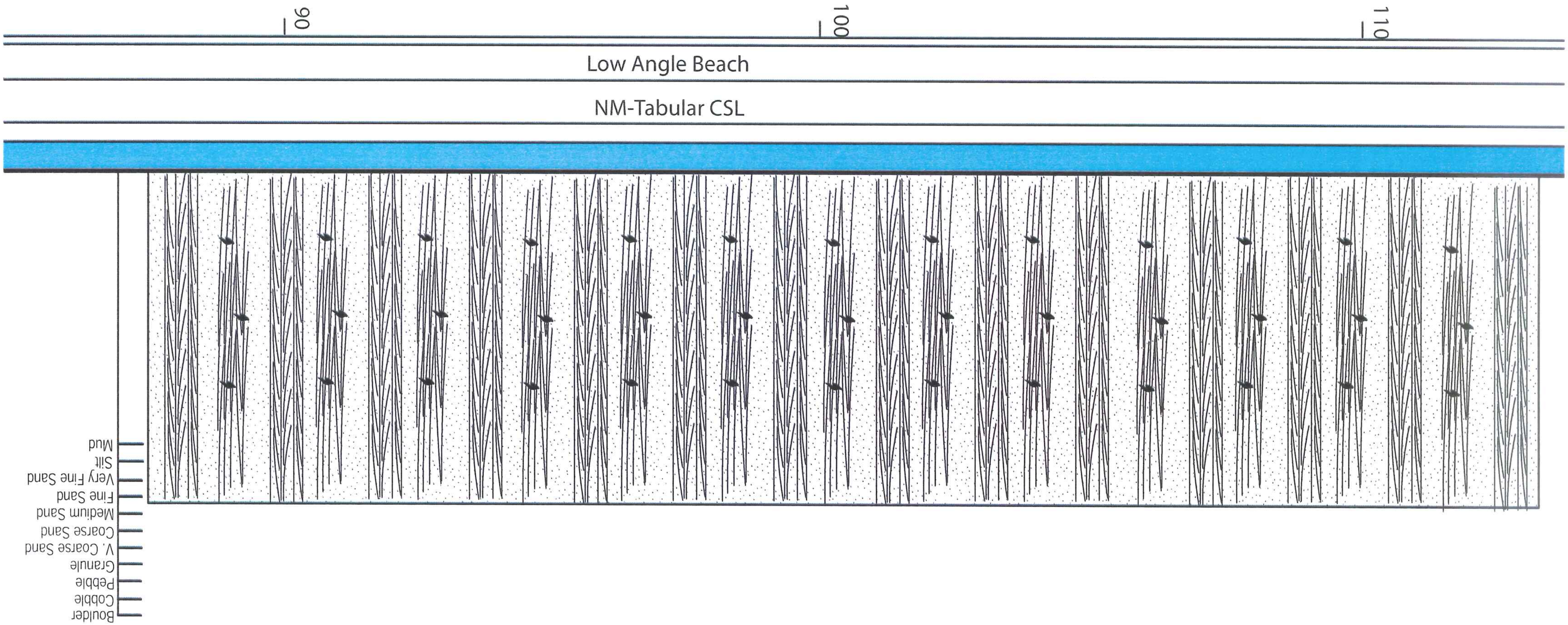
193

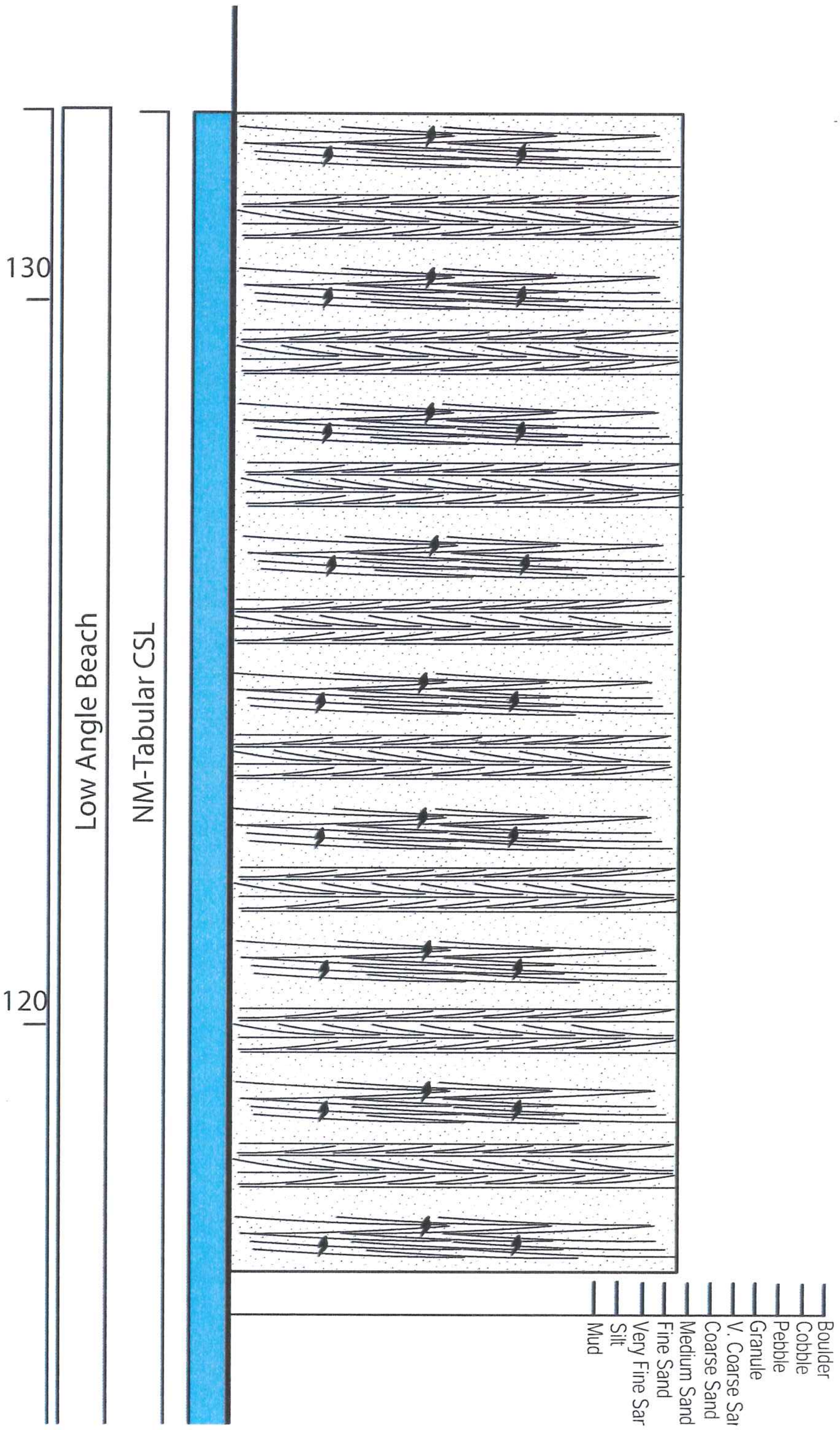

Low Angle Coarse Grained Beach
AM-Tabular CSL
- 3% Feldspar sporadic (vc sand)
- 5% Feldspar (Granule)
- Contact erosional, irregular (over 10cm)
- Coarser clast supported in places (vc sand t-
vc pebble) in some places appears to be openwork structure (P335)
- Some v small slump structures apparent in places, T57 (Pebble samples)
- Contact irregular erosional
- Clasts at surface (Granule to cobble) Mostly qtz, qtzite, dark brown m sst
- Contact irregular-sharp, erosional (Over 10cm)
- Isloated Feldspar (Granule) 5%
- Contact sharp (slightly irregular in places approx 10cm in places)
- Scattered Feldspar 7% (vc sand)
- Feldspar rich beds alternating with quartz beds over 5m (Gradational contact)
- GPS 049 (elevation 1554m) First incursion of feldspar, scolithos bioturbation
- Start section (Southern slope of Handsley Gully above tents)
3m
Scale
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder
Strat 11
Knobhead (Handsley Valley)
25/01/2008
Altar Mountain Sandstone


20
10
Mud Flat
Tidal Estuary
Low Angle Beach
TC-FDL
TC-SML
WG-Tabular CSL
- P342, T59, Syneresis cracks
- Greyish black speckled/mottled
- P341, Dark greyish green, quite speckled
- Very mottled appearence
- P340 minor burrowing
- dark grey/black fissile, isolated cream/white vf sand layers
- Mottled, v well sorted, white, flecks of green
- Pale blue/green, v well sorted, fissile
- TCsst
- Base of Terra Cotta Siltstone
- WGSst
- V well sorted Qtz sand, white, Heimdallia, Isolated Feldspar
- Start Section, Nth flank of Knobhead (GPS 051, Elevation 1319m)
3m
Scale
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder
Strat 12
Knobhead (Handsley Valley)
26th Jan 2008
New Mountain Sandstone
Terra Cotta Siltsone
Windy Gully Sandstone

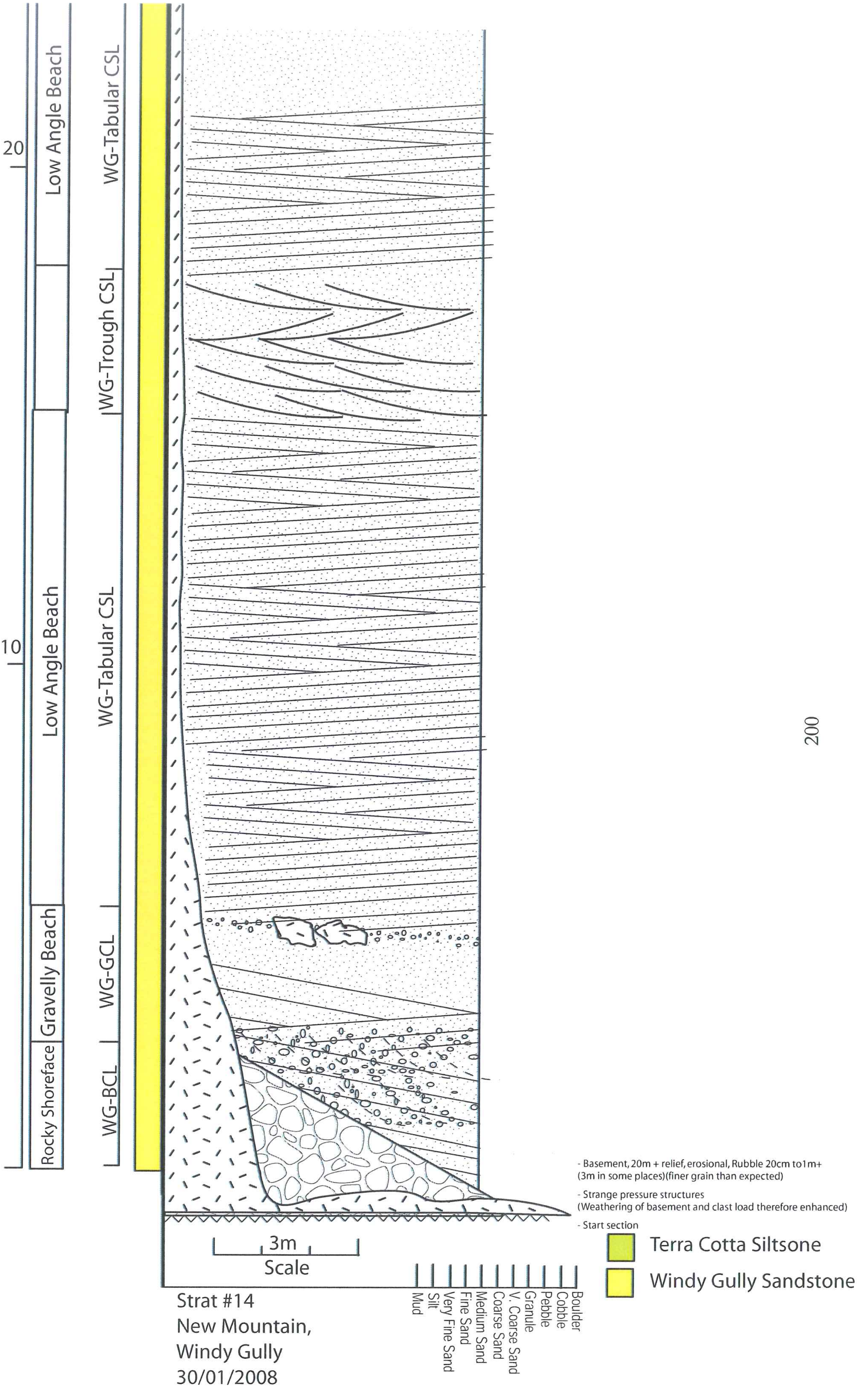

50
40
30
Low Angle Beach
Rubbly Beach
Mud Flat
NM-Tabular CSL
NM-BCL& NM-GCL
TC-FDL
- Slightly pink with thin green laminae (mm scale), Ripples (1cm) T62
- Greenish tinge with rusty red streaking
- GPS 054, Some slumping on Xbeds, Start of Scolithos in forsets
- 5% Feldspar, Heimdallia layers, mod well sorted
- T 53 (X2) P 347-348, Base of N. Mtn. Sst.
isolated vf sand - c silt grey/green biscuits (3-15 cm diameter)
- Windy Gully Erosion Surface
- P346, GPS053, Elevation 1307m, Upper contact of Terra Cotta
- creamy grey, fissile
- v fine lam, turning black, syneresis Cracks
- GPS 052
- P343, 344, 345, Vc pebble to cobble bed, some flat-lensoidal
- Greyish green
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder

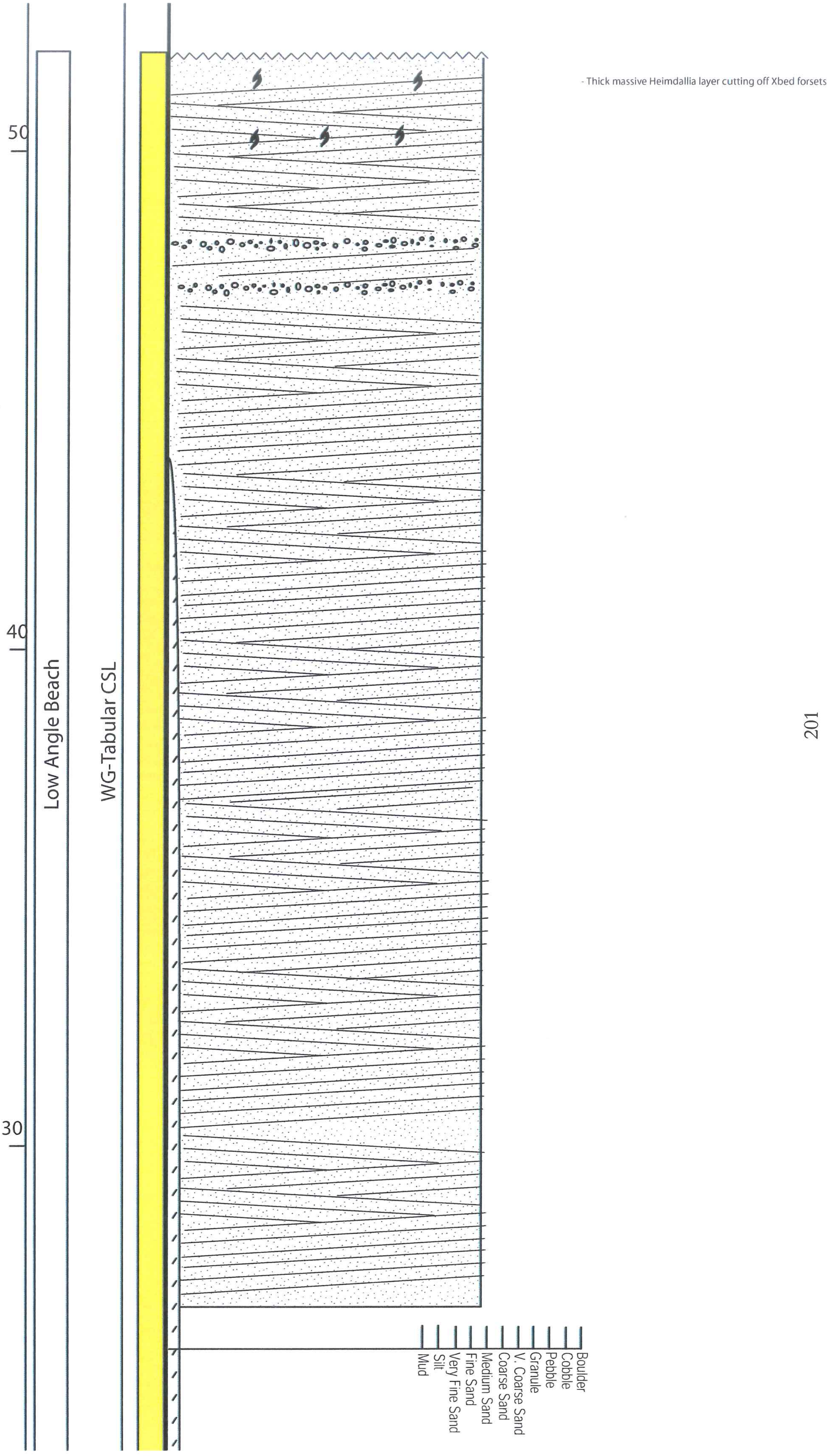

60
70
80
Low Angle Beach
NM-Tabular CSL
Mud
Silt
Very Fine San
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sar
Granule
Pebble
Cobble
Boulder


90
100
110
Low Angle Beach
NM-Tabular CSL
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder

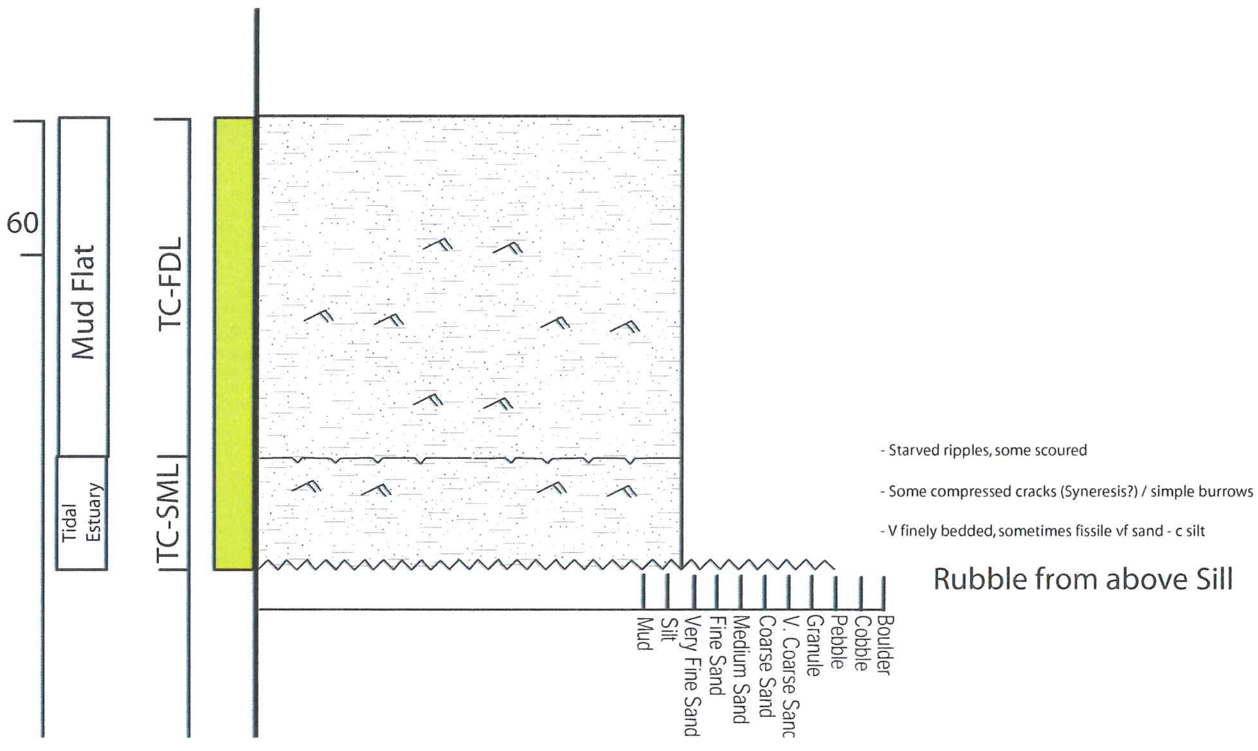


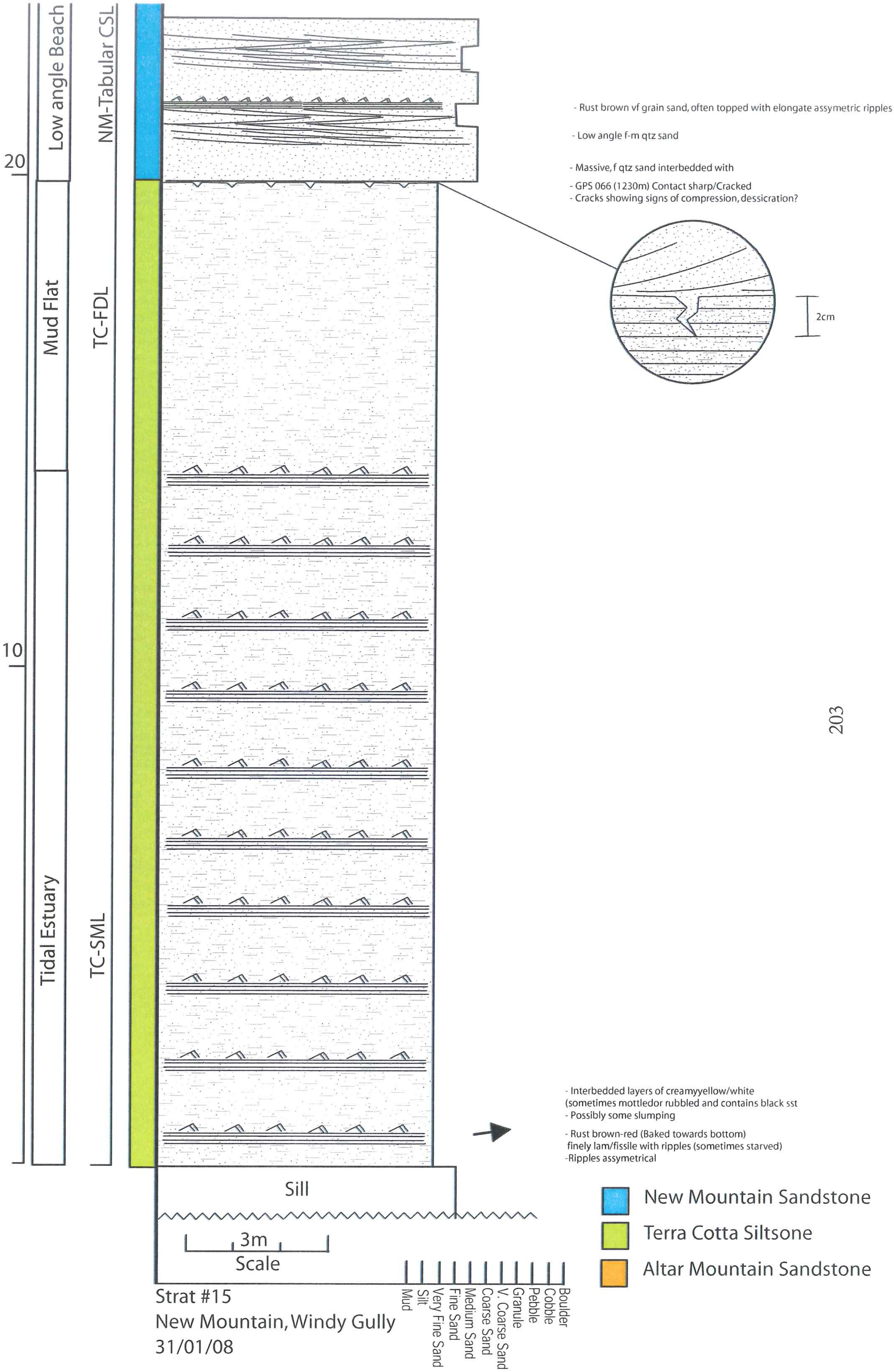
- N Mtn. Sst cut off by Sill, do not see Odin Arcose

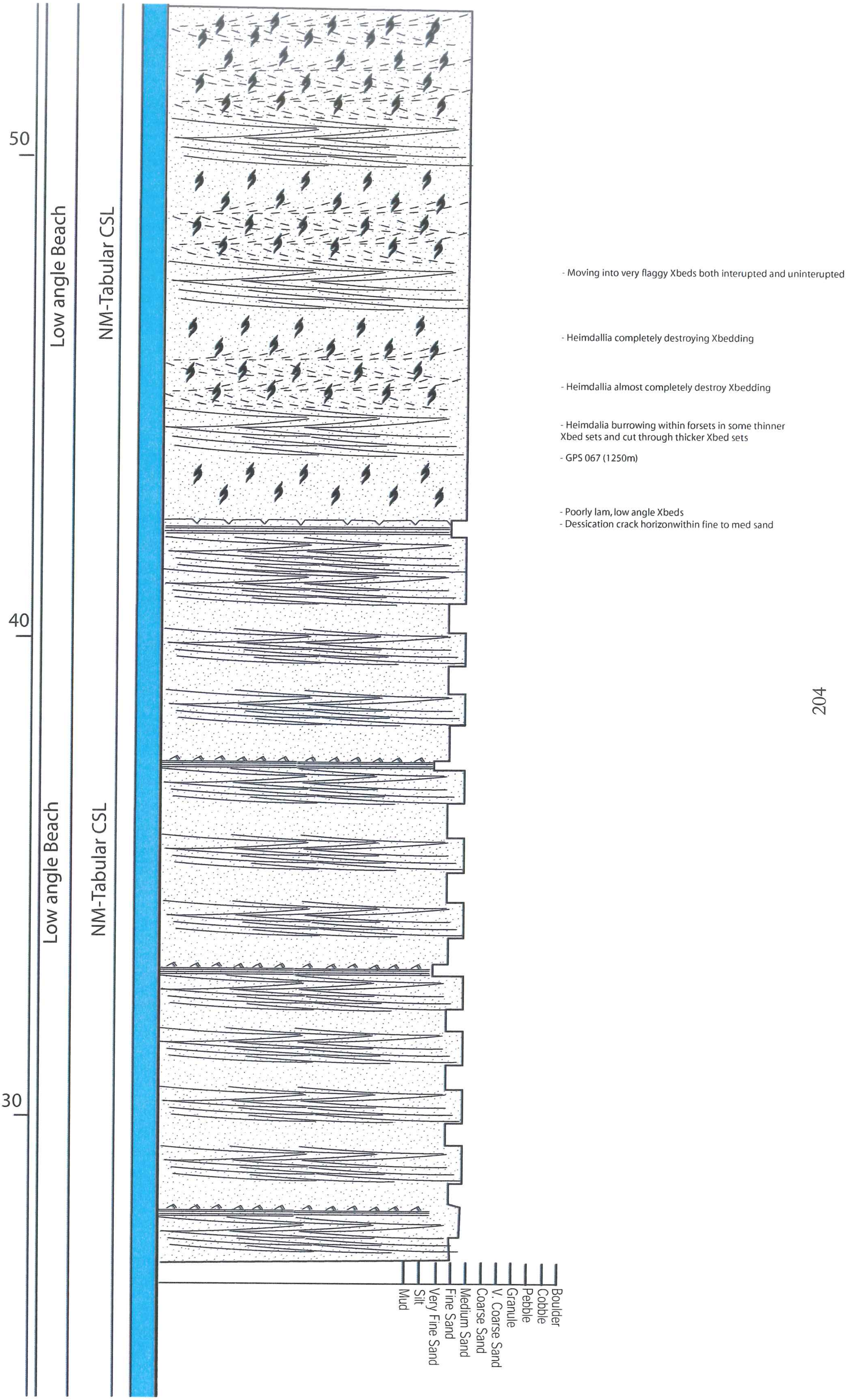

20
10
Low Angle Beach
Low Angle Beach
Gravelly Beach
Rocky Shoreface
WG-Tabular CSL
WG-Trough CSL
WG-Tabular CSL
WG-GCL
WG-BCL
- Basement, 20m + relief, erosional, Rubble 20cm to1m+
(3m in some places)(finer grain than expected)
- Strange pressure structures
(Weathering of basement and clast load therefore enhanced)
- Start section
Terra Cotta Siltsone
Windy Gully Sandstone
3m
Scale
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder
Strat #14
New Mountain,
Windy Gully
30/01/2008

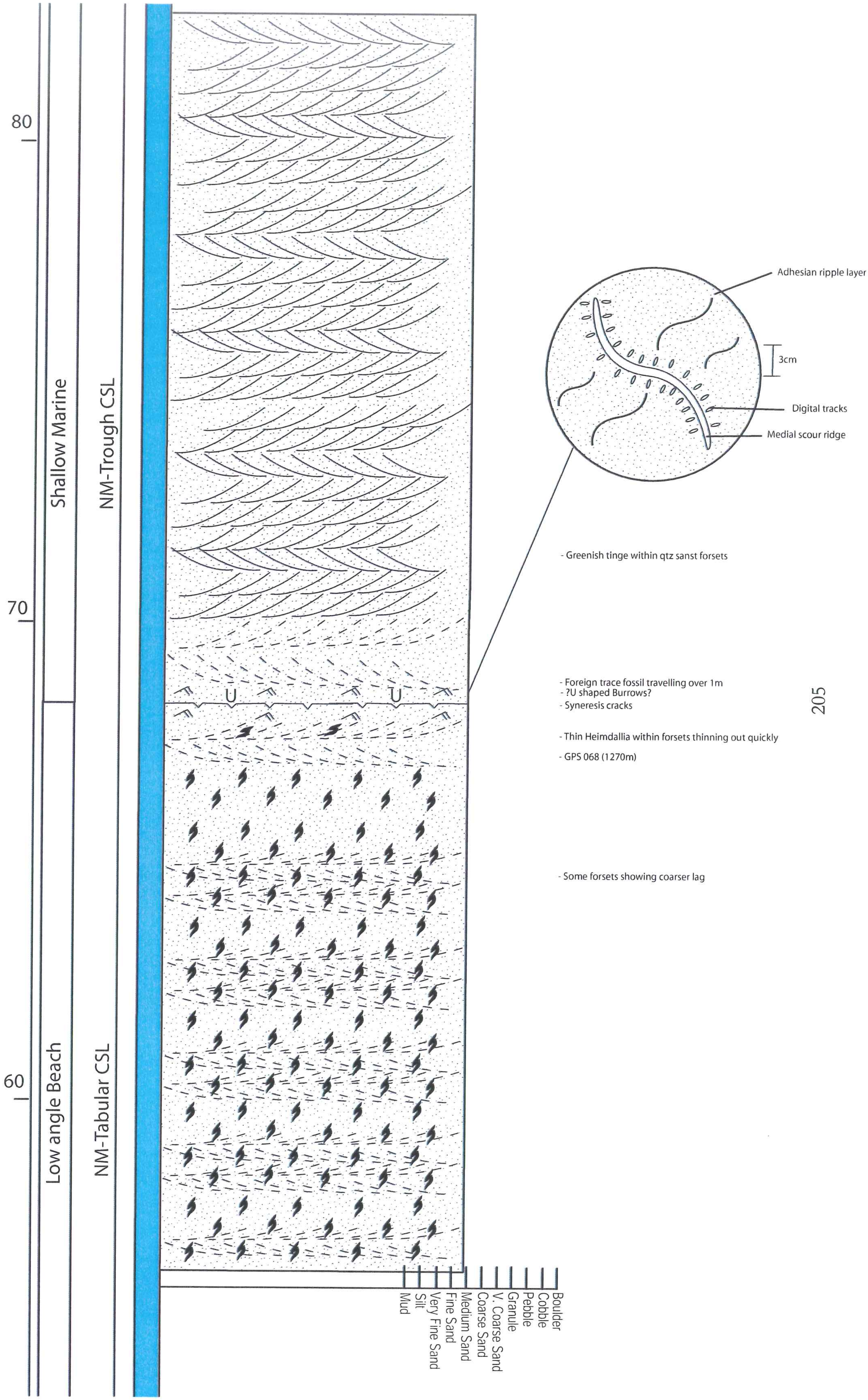


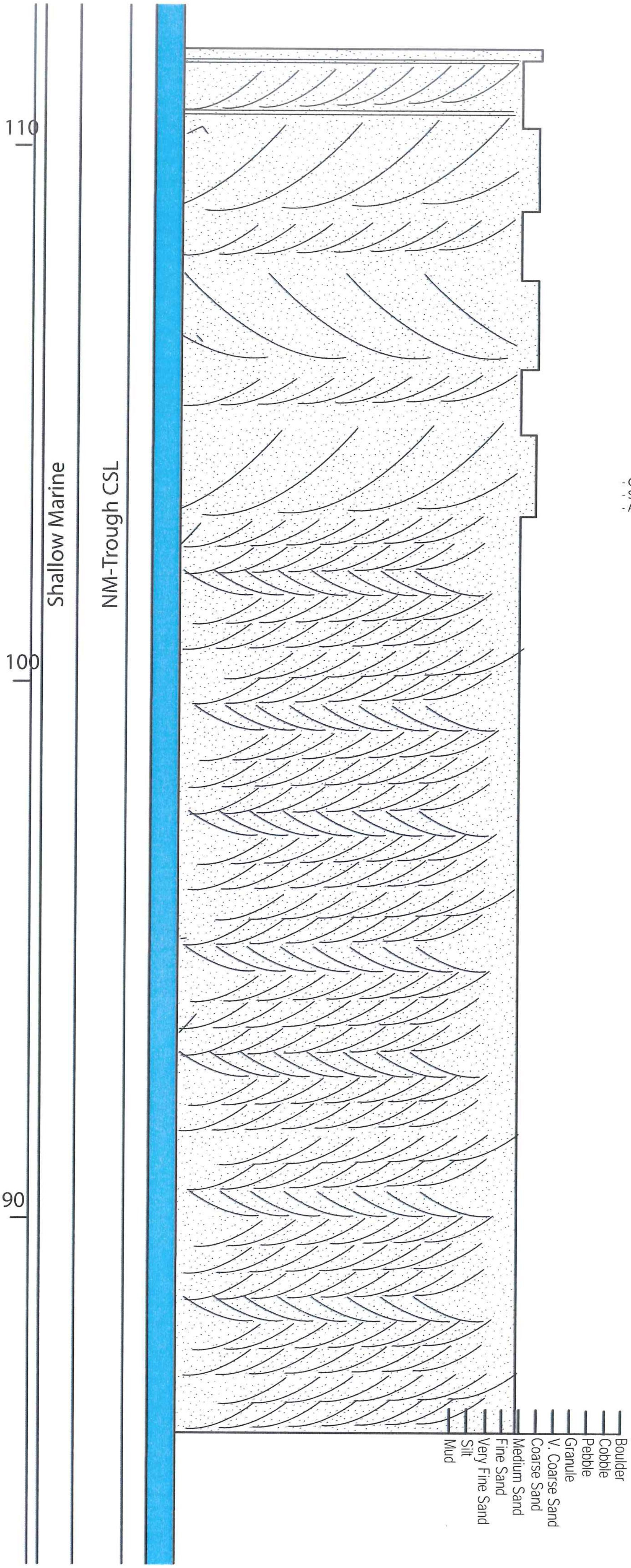
- Thick massive Heimdallia layer cutting off Xbed forsets
50
40
30
Low Angle Beach
WG-Tabular CSL
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder


60
Mud Flat
Tidal Estuary
TC-FDL
TC-SML
- Starved ripples, some scoured
- Some compressed cracks (Syneresis?) / simple burrows
- V finely bedded, sometimes fissile vf sand - c silt
Rubble from above Sill
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder

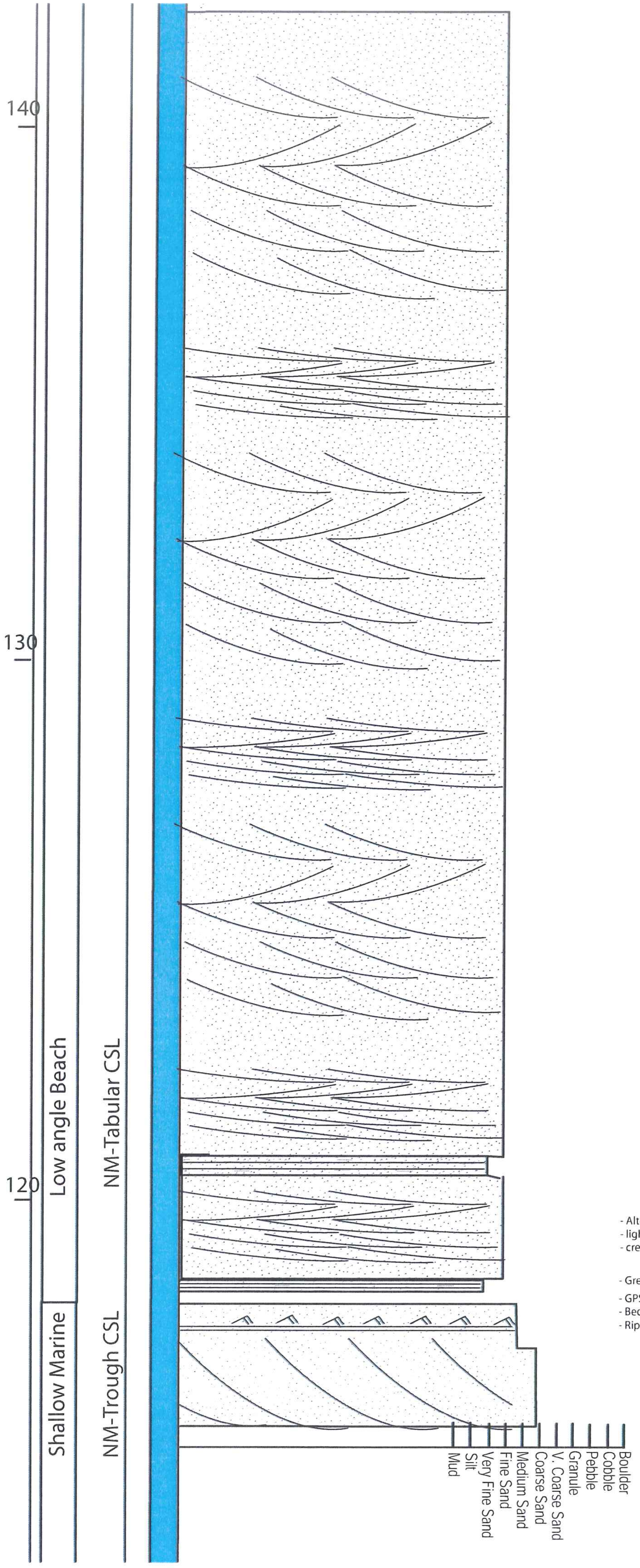

Low angle Beach
Mud Flat
Tidal Estuary
NM-Tabular CSL
TC-FDL
TC-SML
20
10
- Rust brown vf grain sand, often topped with elongate assymetric ripples
- Low angle f-m qtz sand
- Massive, f qtz sand interbedded with
- GPS 066 (1230m) Contact sharp/Cracked
- Cracks showing signs of compression, dessication?
2cm
- Interbedded layers of creamyyellow/white
(sometimes mottledor rubbled and contains black sst
- Possibly some slumping
- Rust brown-red (Baked towards bottom)
finely lam/fissile with ripples (sometimes starved)
-Ripples assymetrical
Sill
3m
Scale
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder
New Mountain Sandstone
Terra Cotta Siltsone
Altar Mountain Sandstone
Strat #15
New Mountain, Windy Gully
31/01/08


50
40
30
Low angle Beach
NM-Tabular CSL
Low angle Beach
NM-Tabular CSL
- Moving into very flaggy Xbeds both interupted and uninterupted
- Heimdallia completely destroying Xbedding
- Heimdallia almost completely destroy Xbedding
- Heimdalia burrowing within forsets in some thinner Xbed sets and cut through thicker Xbed sets
- GPS 067 (1250m)
- Poorly lam, low angle Xbeds
- Dessication crack horizonwithin fine to med sand
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder


80
70
60
Shallow Marine
NM-Trough CSL
Low angle Beach
NM-Tabular CSL
U
U
Adhesian ripple layer
3cm
Digital tracks
Medial scour ridge
- Greenish tinge within qtz sanst forsets
- Foreign trace fossil travelling over 1m
- ?U shaped Burrows?
- Syneresis cracks
- Thin Heimdallia within forsets thinning out quickly
- GPS 068 (1270m)
- Some forsets showing coarser lag
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder

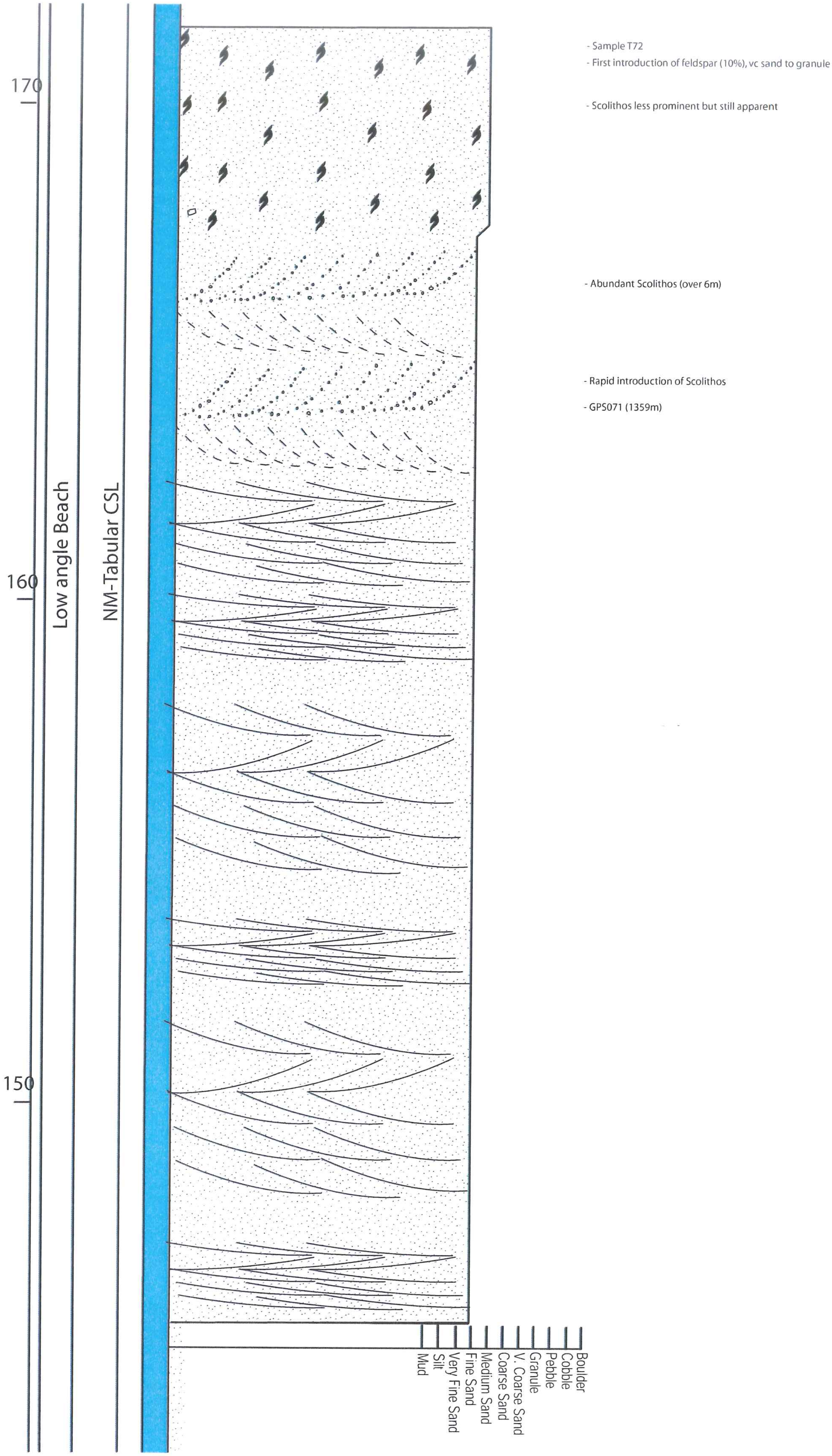


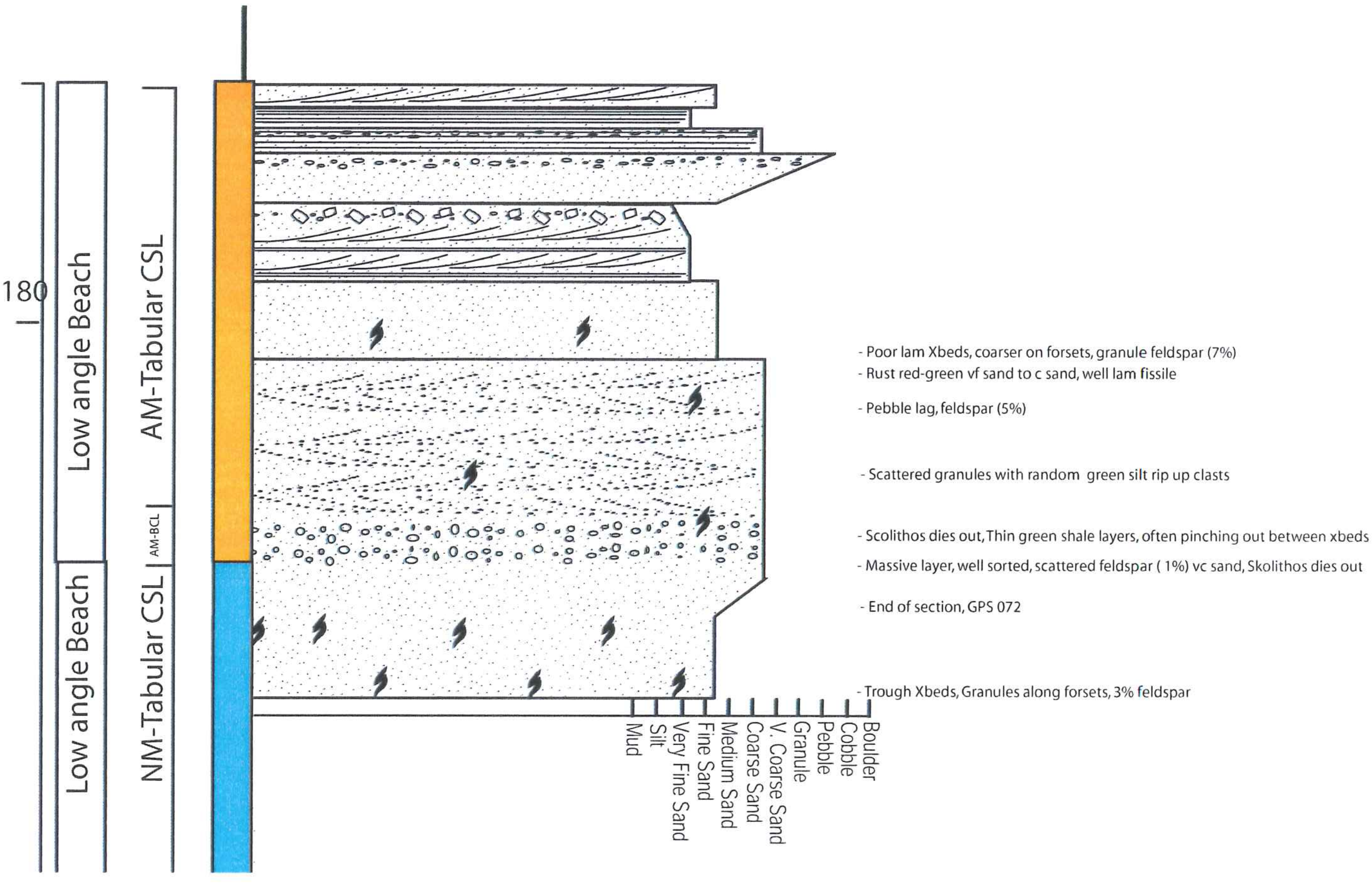
- GPS 069 (1303m) Xbeds becoming coarser and steeper dip
- Steeper dip towards West in coarser beds
- Alternating med and coarse sand Xbeds (Up to 2m)

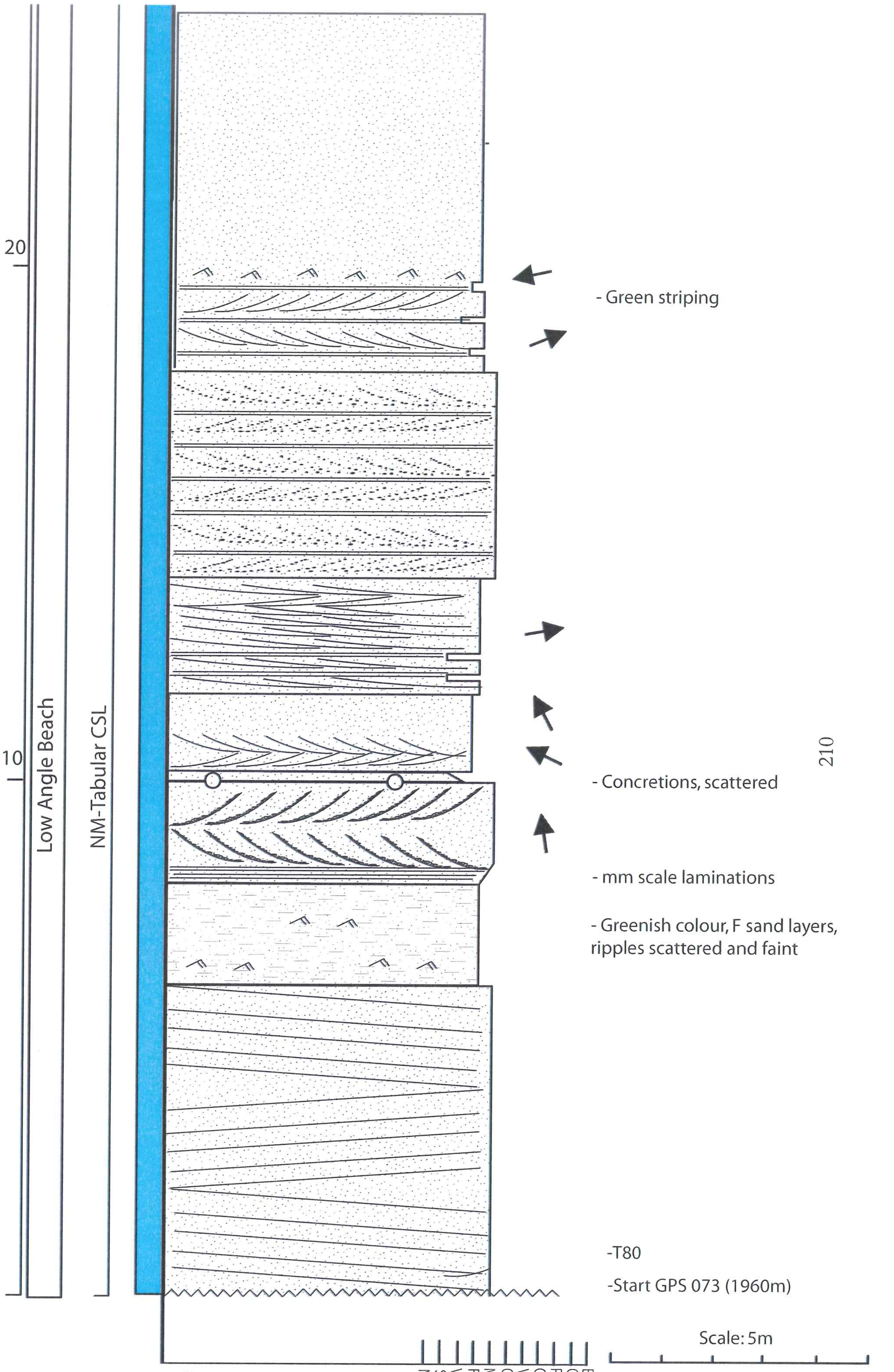


- Alternating beds of;
- light green vf-m qtz sand
- cream, well sorted, m qtz sand

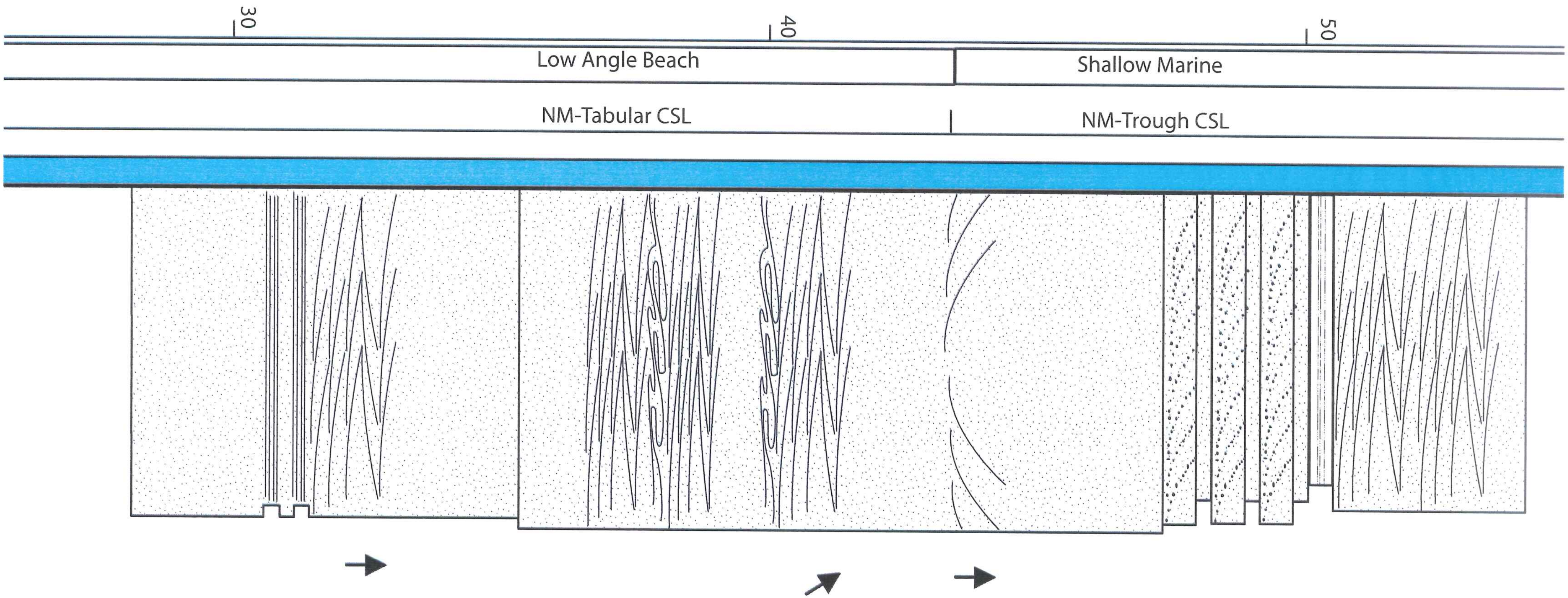
- Green shale layer, fissile , well laminated
- GPS 070 (1314m)
- Beds becoming very green not only along forsets but throughout
- Ripples, Assymetrical (Heading south)

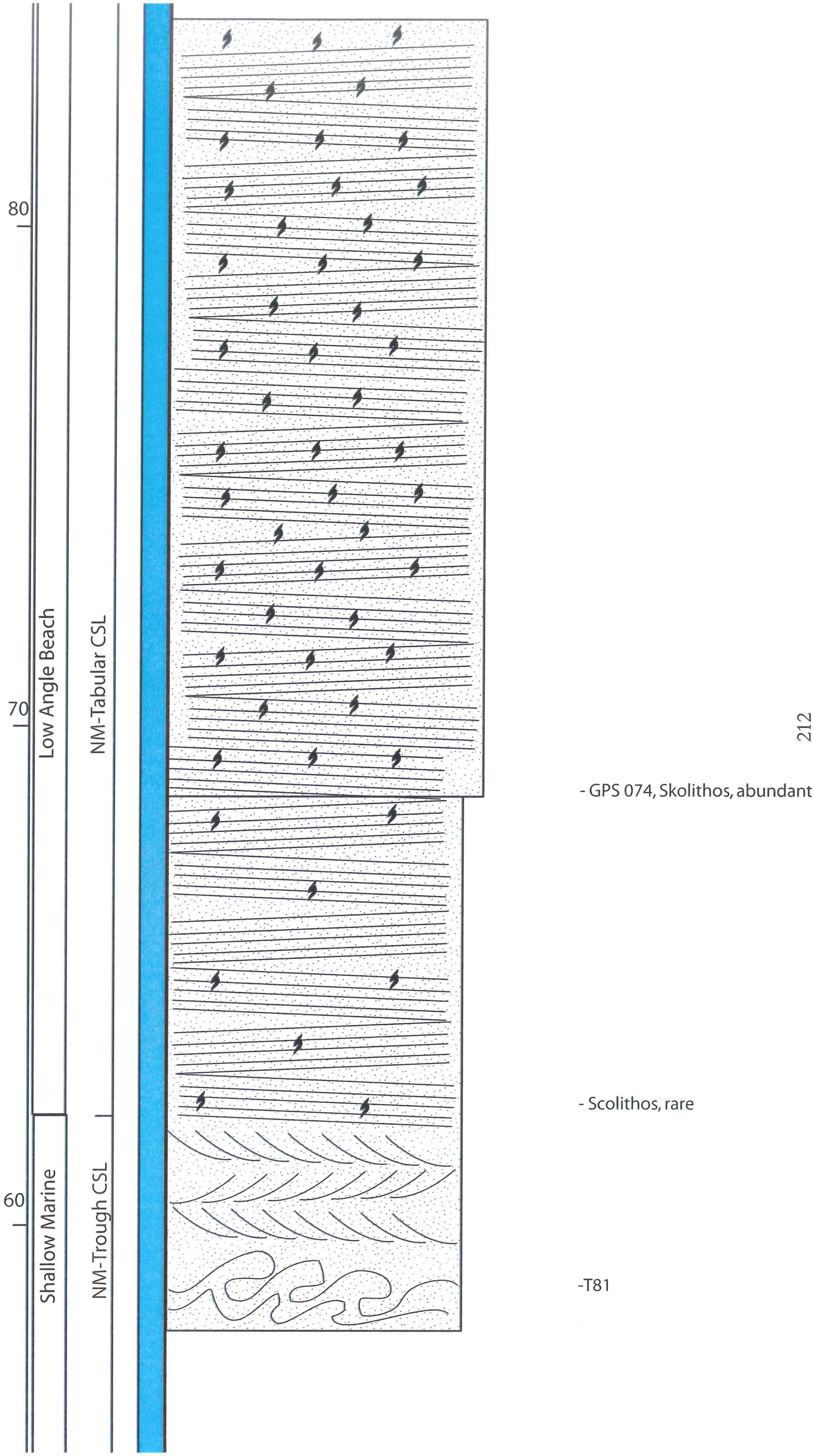

- Sample T72
- First introduction of feldspar (10%), vc sand to granule
- Scolithos less prominent but still apparent
- Abundant Scolithos (over 6m)
- Rapid introduction of Scolithos
- GPS071 (1359m)
170
160
150
Low angle Beach
NM-Tabular CSL
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder

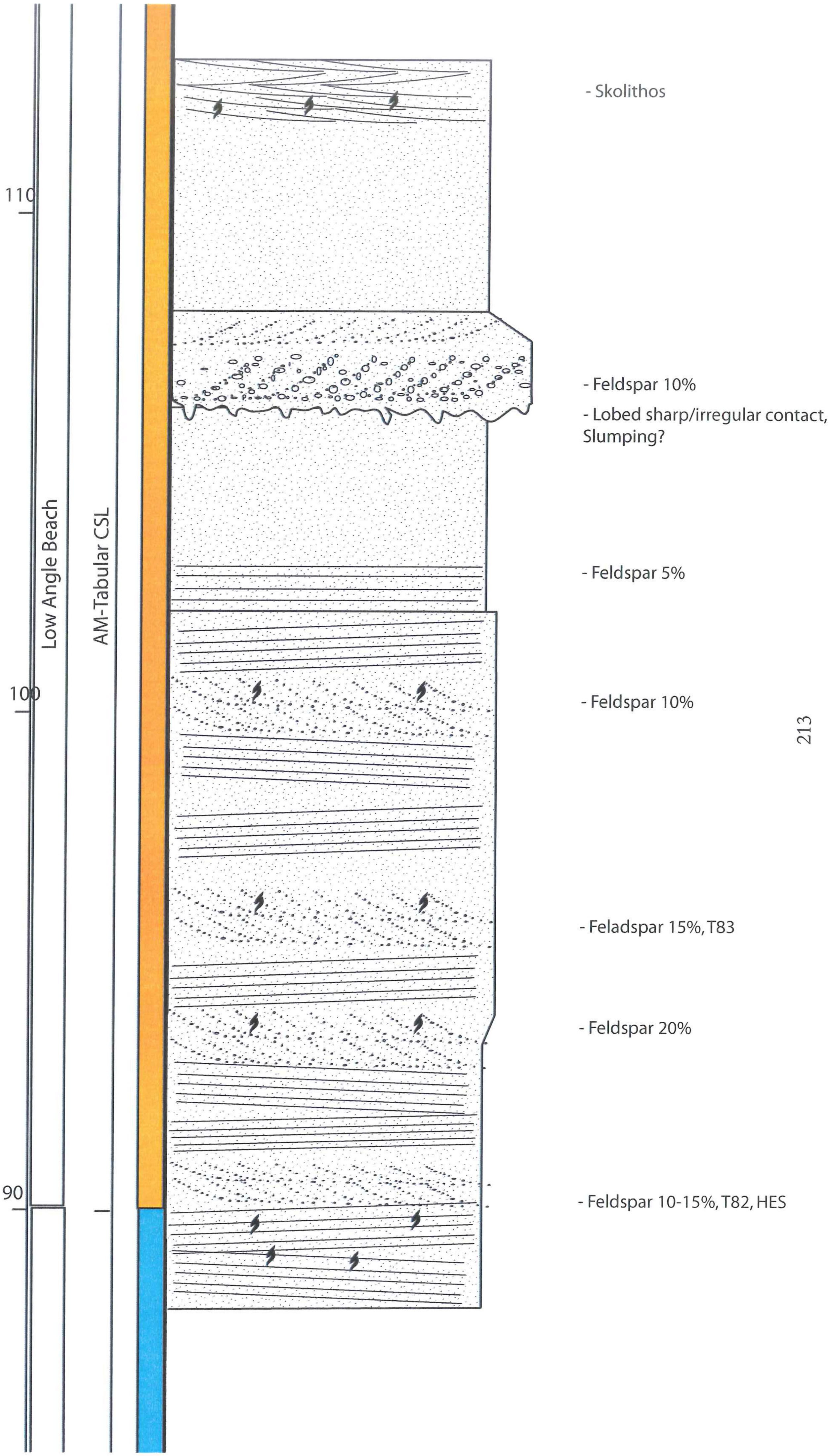

180
Low angle Beach
Low angle Beach
AM-Tabular CSL
AM-BCL
NM-Tabular CSL
- Poor lam Xbeds, coarser on forsets, granule feldspar (7%)
- Rust red-green vf sand to c sand, well lam fissile
- Pebble lag, feldspar (5%)
- Scattered granules with random green silt rip up clasts
- Scolithos dies out, Thin green shale layers, often pinching out between xbeds
- Massive layer, well sorted, scattered feldspar (1%) vc sand, Skolithos dies out
- End of section, GPS 072
- Trough Xbeds, Granules along forsets, 3% feldspar
Mud
Silt
Very Fine Sand
Fine Sand
Medium Sand
Coarse Sand
V. Coarse Sand
Granule
Pebble
Cobble
Boulder

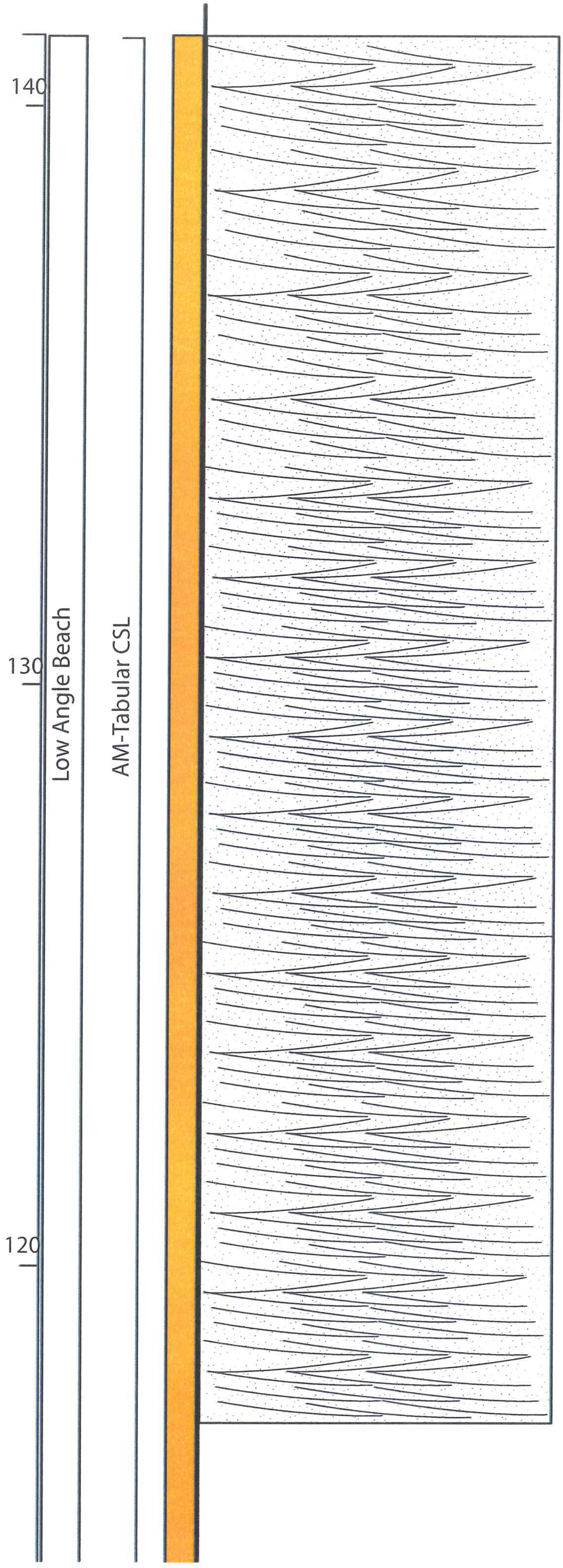


Strat #16
Rotunda
02/02/08


30
40
50
Low Angle Beach
Shallow Marine
NM-Tabular CSL
NM-Trough CSL


80
70
60
Low Angle Beach
Shallow Marine
NM-Tabular CSL
NM-Trough CSL
- GPS 074, Skolithos, abundant
- Scolithos, rare
-T81


110
100
90
Low Angle Beach
AM-Tabular CSL
- Skolithos
- Feldspar 10%
- Lobed sharp/irregular contact, Slumping?
- Feldspar 5%
- Feldspar 10%
- Feladspar 15%, T83
- Feldspar 20%
- Feldspar 10-15%, T82, HES



- End section, GPS 067

Appendix A2: Paleocurrent Data

Windy Gully Sst
Terra Cotta sst
New Mountain Sst
Altar Mountain

Date	Location	Bearing	Dip	X-Bed Thickness (m)	Other	Magnetic correction Deg/min	New Strike (Deg)	Dip Direction/paloeflow	Paleoflow
14/01/2008	Nibelungen Valley								
		130/25°S	25	0.45	MAB	151.47	281	191	
		121/3°S	3	0.4			272	182	
		028/21°SW	21	0.4			179	269	
		136° W axis		33m wide, 2.4deep	Trough (MAB)		287	287	287
		130/10°W	10		Parting Lineations on forsets		139	229	
		128/12°W			Trough axis		279	279	279
		092/12°N	12	0.6	GPS 015 at 5m		243	333	
		121/10°N	10	0.8	at 8m, Diplicnites		272	2	
		054/5°NW	5	2			205	295	
		144/14°SW	14	0.4	GPS 016?		295	234	
		095/6°S	6	0.2	GPS 016?		246	156	
15/01/2008	Nibelungen Valley								
		115/14°S-SE	14	unknown	Contact?	151.52	267	177	
		136/8°S	8				288	226	
		128/4°N-NW	4	unknown	at 11m		280	10	
		054/28°W	28	1-2m	at 14m		206	324	
		000/20°SW	20	unknown	at 17m		152	242	
		042/16° W-SW	16	unknown	at 18m		194	284	
		011/4°SW	4	1	GPS 020		163	253	
		038/8°W	8	unknown	GPS 020		190	280	
		128/12°W	12	15m wide, 3m+ deep	Trough		279	279	
		090/2°SE	2		At top of ridge		242	152	
16/01/2008					Poor weather - no data				
17/01/2008	Moving N from Camp								
18/01/2008	Moved Camp								
19/01/2008	Folkvanger Valley								
		018/29°W	29	2	GPS 029 - Start X-section	152.29	170	260	
		015/13°W	13	unknown			167	257	
		029/22°W	22	unknown			181	271	
		014/22°W	22	unknown			166	256	
		008/21°W	21	unknown			160	250	
		unknown		0.3-0.4	GPS 034 - New X-section, T39				
20/01/2008	E of Folkvanger Valley								
		unknown		0.15-0.4	Poor X-beds				
		unknown		0.2-0.3	Alternating with above X-beds				
21/01/2008	Moved Camp								
22/01/2008									
23/01/2008	Knobhead - S ridge from base camp								
24/01/2008									
		356/11°SW-W	11	unknown		152.18	148	238	
				0.5					
		NW trend			low angle				
		unknown		2	low angle, concretions				
		034/21°E	21	0.9	steep angle		186	96	
		unknown		0.05-0.30					
25/01/2008	Knobhead								
	S slope of Hadsley Valley								
26/01/2008	N Flank of Handsley Valley					152.08			
		002/5°NW-W	5	unknown			210	300	
27/01/2008						152.25			
		008/4°W	4	unknown	flaggy weathering		160	250	
30/01/2008	New Mountain (Windy Gully)					152.46			
				1-2m+	Trough X-beds				
		058/14°N	14	1-1.5m	Shallow planar, some Heimdallia		266	356	
31/01/2008	New Mountain (Windy Gully)					152.47			
		042/7°W	7	0.3	Low angle, flaggy		194	284	
		049/6°NW	6	1.5			201	291	
		042/7°W	7	0.3	flaggy appearence		194	284	
		068/2°N-NW	2	1	Some forsets coarser on the top		220	310	
		072/3°NW	3	unknown			224	314	
		100/12°N	12	1.5			252	342	
		042/18°W	18	1			194	284	
		066/30°W	30	up to 2m			218	308	
		050/8°W	8	unknown			202	292	
		070/8°W	8	unknown			222	312	
2/02/2008	Rotunda					152.37			
		082/4°N	4	unknown	at 6m		290	20	
		026/10°NW	10	unknown	at 8m		234	324	
		118/24°N	24	1.5	at 11.5m		270	0	
		170/2°E	2	unknown	at 12.2m		322	52	
		158/8°NE	8	unknown	at 18m		310	40	
		090/8°NW	8	unknown	at 40.5m, v large troughs		242	332	
4/02/2008	E of camp, Rotunda	100/4°N	4	0.6	massive alternating with X-beds	152.4	252	342	
		148/9°NE	9	1			300	30	

GPS Waypoints Antarctica 2008

Date (D/M/Y)	Waypoint #	S	E	Elevation (m)
8/01/2008	1	77°30.479'	161°12.545'	1572
9/01/2008	2	77°29.510'	161°09.431'	1507
	3	77°28.136'	161°05.858'	1348
10/01/2008	4	77°30.551'	161°10.321'	1453
	5	77°30.575'	161°10.280'	1432
11/01/2006	6	77°30.128'	161°18.371'	1543
	7	77°35.749'	161°27.701'	1690
13/01/2008	8	77°35.763'	161°27.566'	1692
	9	77°35.814'	161°27.318'	1692
	10	77°35.918'	161°26.672'	1668
14/01/2008	11	77°35.308'	161°21.245'	1440
	12	77°35.343'	161°20.980'	1487
	13	77°35.320'	161°20.716	1527
	14	77°35.309'	161°20.322'	1568
	15	77°35.317'	161°20.350'	1572
	16	77°35.331'	161°20.143'	1597
	17	77°35.432'	161°19.611'	1582
15/01/2008	18	77°36.645'	161°20.179'	1486
	19	77°36.511'	161°18.754'	1548
	20	77°36.500'	161°18.592'	1586
	21	77°36.486'	161°18.445'	1623
	22	77°36.466'	161°18.121'	1661
	23	77°36.796'	161°17.363'	1658
17/01/2008	24	77°35.259'	161°25.416'	1553
	25	77°35.287'	161°25.469'	1569
	26	77°34.783'	161°30.573'	1554
	27	77°34.845'	161°30.799'	1531
	28	77°34.875'	161°29.857'	1552
19/01/2008	29	77°35.260'	160°57.570'	1281
	30	77°35.263'	160°57.550'	1283
	31	77°35.338'	160°57.328'	1334
	32	77°35.538'	160°57.257'	1481
	33	77°35.573'	160°57.660'	1481
	34	77°35.548'	160°57.759'	1470
20/01/2008	35	77°35.334'	161°00.562'	1338
	36	77°35.348'	161°01.001'	1345
	37	77°35.339'	161°00.672'	1337
	38	77°35.371'	161°01.399'	1350
	39	77°35.375'	161°02.715'	1350
	40	77°35.395'	161°05.230'	1409
	41	77°35.426'	161°06.122'	1424
	42	77°35.714'	161°07.483'	1454
	43	77°35.698'	161°07.370	1502
23/01/2008	44	77°55.562'	161°37.203'	1591
	45	77°55.591'	161°37.251'	1618
24/01/2008	46	77°55.591'	161°37.263'	1548
	47	77°55.829'	161°36.665'	1646
25/01/2008	48	77°55.458'	161°38.577'	1404
	49	77°55.831'	161°33.483'	1554
	50	77°55.866'	161°33.495'	1614
26/01/2008	51	77°53.802'	161°40.528	1319
	52	77°53.795'	161°40.314'	1298
	53	77°53.795'	161°40.291'	1307
	54	77°53.774'	161°39.992'	1367
	55	77°53.788'	161°39.605'	1438
	56	77°53.885'	161°41.015'	1150
27/01/2008	57	77°55.540'	161°33.255'	1618
	58	77°55.827'	161°34.342'	1623
	59	77°55.692'	161°35.747'	1654
	60	77°55.480'	161°37.241'	1523
	61	77°55.448'	161°37.486'	1480
	62	77°55.433'	161°37.773'	1446
	63	77°55.409'	161°38.121'	1417
	64	77°55.427'	161°38.437'	1403
30/01/2008	65	77°51.682'	161°14.631'	980
31/01/2008	66	77°52.050'	161°15.397'	1230
	67	77°52.048'	161°15.310'	1250
	68	77°52.042'	161°15.026'	1268
	69	77°52.035'	161°14.482'	1303
	70	77°52.020'	161°14.363'	1314
	71	77°52.009'	161°13.992'	1359
	72	77°51.978'	161°13.879'	1391
2/02/2008	73	78°01.188'	161°36.343'	1960
	74	78°01.216'	161°35.363'	2061
	75	78°01.203'	161°35.157'	2083
	76	78°01.178'	161°34.944'	2145
	77	78°01.174'	161°34.908'	2149
4/02/2008	78	78°01.958'	161°34.363	2013
	79	78°01.977'	161°34.299	2144
	80	78°01.958'	161°34.079'	2127
	81	78°01.953'	161°33.901'	2139
	82	78°01.962'	161°33.500'	2227

Unit	Sample #	Clast Composition														QFL Count	Total Count	Count Type
		Quartz		Feldspar (Pl)		Feldspar (Orth)		Clay		Cement		Lithics		Mica				
		Count	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%			
Altar Mtn	T1	424.0	89.3	29.0	6.1	8.0	1.7	25.0	5.0	0.0	0.0	14.0	2.9	0.0	0.0	475.0	500	Point
NMSst	T2	448.0	99.1	1.0	0.2	0.0	0.0	48.0	9.6	0.0	0.0	3.0	0.7	0.0	0.0	452.0	500	Point
Altar Mtn	T3	356.0	79.6	60.0	13.4	8.0	1.8	53.0	10.6	0.0	0.0	23.0	5.1	0.0	0.0	447.0	500	Point
Altar Mtn	T4	444.0	95.9	5.0	1.1	4.0	0.9	37.0	7.4	0.0	0.0	10.0	2.2	0.0	0.0	463.0	500	Point
WGSst	T5	278.0	97.2	5.0	1.7	2.0	0.7	11.0	3.7	0.0	0.0	1.0	0.3	3.0	1.0	286.0	300	Point
NMSst	T9	244.0	90.4	22.0	8.1	0.0	0.0	30.0	10.0	0.0	0.0	4.0	1.5	0.0	0.0	270.0	300	Point
Altar Mtn	T12	70.0	70.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.0	30.0	0.0	0.0	100.0	100	Pebble
Altar Mtn	T18	64.0	62.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	39.0	37.9	0.0	0.0	103.0	103	Pebble
WGSst	T22	234.0	78.5	60.0	20.1	4.0	1.3	2.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	298.0	300	Point
Altar Mtn	T31	59.0	56.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	46.0	43.8	0.0	0.0	105.0	105	Pebble
Altar Mtn	T34	318.0	81.3	72.0	18.4	0.0	0.0	9.0	2.3	0.0	0.0	1.0	0.3	0.0	0.0	391.0	400	Point
Altar Mtn	T39	424.0	91.0	30.0	6.4	7.0	1.5	34.0	6.8	0.0	0.0	5.0	1.1	0.0	0.0	466.0	500	Point
WGSst	T41	425.0	89.3	15.0	3.2	30.0	6.3	0.0	0.0	24.0	4.8	6.0	1.3	0.0	0.0	476.0	500	Point
WGSst	T42	379.0	81.5	66.0	14.2	9.0	1.9	35.0	7.0	0.0	0.0	11.0	2.4	0.0	0.0	465.0	500	Point
Altar Mtn	T44	413.0	97.6	0.0	0.0	0.0	0.0	77.0	15.4	0.0	0.0	10.0	2.4	0.0	0.0	423.0	500	Point
Altar Mtn	T45	475.0	95.0	21.0	4.2	1.0	0.2	0.0	0.0	0.0	0.0	3.0	0.6	0.0	0.0	500.0	500	Point
NMSst	T61	380.0	76.0	109.0	21.8	9.0	1.8	0.0	0.0	0.0	0.0	2.0	0.4	0.0	0.0	500.0	500	Point
NMSst	T62	342.0	68.4	158.0	31.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	500.0	500	Point
NMSst	T63	424.0	86.2	65.0	13.2	0.0	0.0	8.0	1.6	0.0	0.0	3.0	0.6	0.0	0.0	492.0	500	Point

Appendix B: Lab Data
Appendix B1: Point Counts

Appendix B2: La-ICP-MS Results

T50 analysis ID	spot number	Pb*(ppm)	U(ppm)	atomic Th/U	uncorr'd 206Pb/238U ratio	±%	uncorr'd 207Pb/235U ratio	±%	uncorr'd 207Pb/206Pb ratio	±%	uncorr'd 208Pb/232Th ratio	±%	208Pb corr'd 206Pb*/238U age (Ma)	±	208Pb corr'd 207Pb*/235U age (Ma)	±	208Pb corr'd 207Pb*/206Pb* age (Ma)	±	% 6*/38-7*/35 concordance	%common 206Pb using 208Pb	spot MSWD	selected age (Ma)	±
sample		#VALUE!	U(ppm)	232/238	uncorr'd 206/238	#VALUE!	uncorr'd 207/23	#VALUE!	uncorr'd 207/206	#VALUE!	uncorr'd 208/232	#VALUE!	208Pb corr'd 6/38 age	observed ±1s.e.	208Pb corr'd 7/35 age	observed ±1s.e.	208Pb corr'd 7/6 age	observed ±1s.e.	#VALUE!	#VALUE!	spot MSWD	selected date	±1se
C:\ICPCHEM\1\DATA\palin\090325a\t50-01.d	-0	0.00	318	0.58	0.08614	0.7	0.7206	1.9	0.0607	1.8	0.02811	1.5	537.9	3.8	519.5	12.5	473.0	11.3	104	100.00	3.27	537.9	14.1
C:\ICPCHEM\1\DATA\palin\090325a\t50-02.d	-0	0.00	174	0.34	0.07614	0.8	0.6201	2.7	0.0591	2.6	0.02702	2.1	473.2	3.9	446.1	24.1	326.3	18.4	106	100.00	2.01		
C:\ICPCHEM\1\DATA\palin\090325a\t50-03.d	-0	0.00	119	0.52	0.08801	0.8	0.7364	3.0	0.0607	2.8	0.02851	1.9	544.9	4.3	533.2	18.2	498.0	17.0	102	100.00	1.66	544.9	14.4
C:\ICPCHEM\1\DATA\palin\090325a\t50-04.d	-0	0.00	92	0.50	0.09526	1.1	0.8773	3.2	0.0668	3.0	0.04353	2.1	576.6	6.3	370.9	30.4	0.1	0.0	155	100.00	2.31	576.6	15.8
C:\ICPCHEM\1\DATA\palin\090325a\t50-06.d	-0	0.00	121	0.53	0.08677	0.9	0.7606	2.7	0.0636	2.5	0.02992	1.9	539.0	4.6	515.3	16.1	444.0	13.9	105	100.00	2.30	539.0	14.3
C:\ICPCHEM\1\DATA\palin\090325a\t50-08.d	-0	0.00	62	0.66	0.09376	1.1	0.8044	4.8	0.0622	4.6	0.03081	2.4	581.0	6.5	549.7	29.5	452.3	25.0	106	100.00	1.74	581.0	16.0
C:\ICPCHEM\1\DATA\palin\090325a\t50-09.d	-0	0.00	168	0.58	0.08995	1.4	0.7831	4.0	0.0631	3.8	0.03744	7.3	549.1	8.0	395.4	58.5	0.2	0.0	139	100.00	2.69	549.1	16.0
C:\ICPCHEM\1\DATA\palin\090325a\t50-10.d	-1	0.00	263	0.54	0.08763	0.7	0.7347	2.1	0.0608	2.0	0.02659	1.6	548.4	3.7	569.4	16.5	678.7	18.4	96	100.00	2.20	548.4	14.3
C:\ICPCHEM\1\DATA\palin\090325a\t50-11.d	-1	0.00	184	0.70	0.09200	0.8	0.9986	2.6	0.0787	2.4	0.03438	2.1	560.4	4.6	557.1	27.3	567.5	27.4	101	100.00	1.28	560.4	14.9
C:\ICPCHEM\1\DATA\palin\090325a\t50-12.d	-1	0.00	344	0.56	0.13466	3.7	4.9919	9.3	0.2689	8.6	0.20358	11.3	625.2	31.0	-52.8	-743.8	0.0	0.0	-1183	100.00	6.33		
C:\ICPCHEM\1\DATA\palin\090325a\t50-13.d	-1	0.00	89	0.95	0.08896	1.1	0.8939	4.3	0.0729	4.2	0.03172	2.0	545.2	6.0	489.8	37.8	278.5	23.5	111	100.00	2.25	545.2	15.0
C:\ICPCHEM\1\DATA\palin\090325a\t50-14.d	-1	0.00	145	0.71	0.07908	0.8	0.6438	2.7	0.0590	2.6	0.02657	1.7	497.4	3.8	448.2	18.7	257.6	11.6	111	100.00	1.85		
C:\ICPCHEM\1\DATA\palin\090325a\t50-15.d	-1	0.00	443	0.46	0.08744	0.6	0.7219	1.5	0.0599	1.4	0.02898	1.7	544.6	3.3	520.7	15.1	446.3	13.1	105	100.00	3.34	544.6	14.1
C:\ICPCHEM\1\DATA\palin\090325a\t50-16.d	-1	0.00	657	1.71	0.07157	0.9	0.8964	2.4	0.0908	2.2	0.02583	1.4	482.6	4.4	367.3	29.4	7/6 not converged	4.4	131	100.00	8.87		
C:\ICPCHEM\1\DATA\palin\090325a\t50-17.d	-1	0.00	703	0.65	0.07763	0.8	0.6521	1.6	0.0609	1.4	0.02518	1.6	491.8	3.7	483.4	11.2	500.5	11.0	102	100.00	6.53		
C:\ICPCHEM\1\DATA\palin\090325a\t50-18.d	-1	0.00	507	0.66	0.07732	0.9	0.7483	1.6	0.0702	1.3	0.02538	1.8	486.0	4.1	534.6	12.3	786.6	15.5	91	100.00	5.59		
C:\ICPCHEM\1\DATA\palin\090325a\t50-19.d	-1	0.00	270	0.80	0.08208	0.7	0.6732	2.4	0.0595	2.3	0.02587	1.4	520.3	3.4	509.7	15.3	519.5	15.3	102	100.00	1.94	520.3	13.5
C:\ICPCHEM\1\DATA\palin\090325a\t50-20.d	-2	0.00	455	0.32	0.09017	1.6	0.7853	2.1	0.0632	1.3	0.02871	1.7	556.7	8.8	577.3	17.9	663.7	18.1	96	100.00	19.11	556.7	16.5
C:\ICPCHEM\1\DATA\palin\090325a\t50-21.d	-2	0.00	149	0.58	0.09157	0.7	0.7092	3.1	0.0562	3.0	0.02878	2.0	570.0	4.0	534.9	17.7	412.6	14.2	107	100.00	1.51	570.0	14.9
C:\ICPCHEM\1\DATA\palin\090325a\t50-22.d	-2	0.00	72	0.91	0.17571	1.0	1.8271	3.2	0.0754	3.0	0.05739	2.1	1063.0	10.4	945.5	42.2	751.2	35.9	112	100.00	5.37	751.2	28.7
C:\ICPCHEM\1\DATA\palin\090325a\t50-23.d	-2	0.00	618	0.43	0.08322	1.0	0.7182	1.5	0.0626	1.1	0.02964	1.6	518.6	5.2	489.1	10.2	390.5	7.8	106	100.00	8.18	518.6	14.0
C:\ICPCHEM\1\DATA\palin\090325a\t50-24.d	-2	0.00	798	0.77	0.07889	0.7	0.9298	4.6	0.0855	4.5	0.03341	3.8	486.7	4.1	404.8	48.1	7/6 not converged	9.5	120	100.00	8.34		
C:\ICPCHEM\1\DATA\palin\090325a\t50-25.d	-2	0.00	117	0.78	0.08191	1.1	0.6210	3.1	0.0550	2.9	0.02526	2.0	517.6	5.7	494.5	20.9	433.5	18.4	105	100.00	1.67	517.6	14.2
C:\ICPCHEM\1\DATA\palin\090325a\t50-26.d	-2	0.00	95	0.60	0.08365	1.0	0.6642	3.7	0.0576	3.6	0.02662	2.3	523.7	5.1	507.4	25.6	464.1	23.6	103	100.00	1.25	523.7	14.1
C:\ICPCHEM\1\DATA\palin\090325a\t50-27.d	-2	0.00	243	0.59	0.08507	0.7	0.6763	2.7	0.0577	2.6	0.02744	1.3	531.5	3.9	499.8	15.9	388.9	12.8	106	100.00	2.68	531.5	13.9
C:\ICPCHEM\1\DATA\palin\090325a\t50-29.d	-2	0.00	207	0.58	0.07986	0.8	0.6402	2.5	0.0581	2.4	0.02568	1.7	503.9	4.1	482.4	13.9	429.2	12.3	104	100.00	2.07	503.9	13.3
C:\ICPCHEM\1\DATA\palin\090325a\t50-30.d	-3	0.00	176	0.67	0.09290	1.4	0.9060	2.8	0.0707	2.4	0.03334	1.8	574.5	8.1	539.1	25.4	440.2	21.0	107	100.00	6.13	574.5	16.6
C:\ICPCHEM\1\DATA\palin\090325c\t50-31.d	-3	0.00	477	0.49	0.08589	0.7	0.7277	2.1	0.0615	1.9	0.02899	1.9	531.5	3.6	514.1	13.2	453.8	11.7	103	100.00	4.02	531.5	8.4
C:\ICPCHEM\1\DATA\palin\090325c\t50-32.d	-3	0.00	464	0.83	0.08818	1.4	1.0118	3.9	0.0832	3.6	0.03582	3.7	533.7	7.9	477.6	44.8	256.5	26.4	112	100.00	12.24	533.7	11.0
C:\ICPCHEM\1\DATA\palin\090325c\t50-33.d	-3	0.00	7300	1.36	0.26022	2.8	3.6624	3.9	0.1021	2.7	0.04375	1.8	1617.8	40.6	2071.5	35.9	2573.9	27.0	78	100.00	3.74	2573.9	117.5
C:\ICPCHEM\1\DATA\palin\090325c\t50-34.d	-3	0.00	451	0.47	0.08924	0.9	0.6962	1.8	0.0566	1.6	0.02910	1.7	552.7	5.0	512.5	16.7	352.6	12.1	108	100.00	6.43	552.7	9.4
C:\ICPCHEM\1\DATA\palin\090325c\t50-35.d	-3	0.00	166	0.75	0.08578	1.0	0.7144	2.9	0.0604	2.7	0.02639	2.5	535.5	5.5	552.7	21.8	643.3	23.9	97	100.00	2.36	535.5	9.5
C:\ICPCHEM\1\DATA\palin\090325c\t50-36.d	-3	0.00	56	0.40	0.08782	1.1	0.7231	5.1	0.0597	4.9	0.02761	3.8	544.7	6.1	543.0	26.8	548.0	26.5	100	100.00	1.33	544.7	9.9
C:\ICPCHEM\1\DATA\palin\090325c\t50-37.d	-3	0.00	230	0.61	0.08453	0.9	0.6567	2.3	0.0563	2.2	0.02829	1.7	523.7	4.4	457.7	16.1	161.6	6.4	114	100.00	3.15	523.7	8.7
C:\ICPCHEM\1\DATA\palin\090325c\t50-38.d	-3	0.00	292	0.47	0.08931	0.6	0.7256	2.2	0.0589	2.1	0.02987	1.8	552.4	3.5	516.2	14.5	376.4	11.1	107	100.00	2.16	552.4	8.7
C:\ICPCHEM\1\DATA\cooper\041019\Re65-05.D	5-	0.00	327	0.12	0.16229	0.5	1.7483	1.8	0.0781	1.7	0.07041	4.9	963.9	4.9	970.4	14.8	987.2	14.5	99	100.00	2.51	963.9	4.9
C:\ICPCHEM\1\DATA\cooper\041019\Re48-04.D	8-	0.00	430	0.38	0.16129	0.5	1.7124	1.1	0.0770	1.0	0.05120	1.0	964.3	4.9	990.8	9.1	1056.5	8.7	97	100.00	4.35	964.3	4.9
C:\ICPCHEM\1\DATA\cooper\041019\Re101-07.D	01	0.00	176	1.73	0.16038	0.5	1.6508	1.3	0.0747	1.2	0.04937	0.6	966.1	5.1	946.9	27.2	930.4	26.7	102	100.00	4.58	966.1	5.1
C:\ICPCHEM\1\DATA\cooper\041019\Re77-06.D	7-	0.00	146	0.78	0.16216	0.6	1.7519	1.8	0.0784	1.7	0.04524	1.8	983.8	5.6	1100.2	18.3	1351.5	19.8	89	100.00	1.89	983.8	5.6
C:\ICPCHEM\1\DATA\cooper\041019\Re89-06.D	9-	0.00	442	0.21	0.16764	0.8	1.7248	1.4	0.0746	1.2	0.05234	1.3	999.8	7.0	1009.8	9.8	1035.1	8.6	99	100.00	6.44	999.8	7.0
C:\ICPCHEM\1\DATA\cooper\041019\Re16-02.D	6-	0.00	105	0.72	0.17459	1.4	2.1606	3.0	0.0898	2.7	0.06740	2.4	1013.1	14.1	921.5	41.9	720.0	34.8	110	100.00	8.53	720.0	14.1
C:\ICPCHEM\1\DATA\cooper\041019\Re50-04.D	0-	0.00	65	0.47	0.18988	0.7	1.9253	2.3	0.0735	2.2	0.06209	1.5	1117.7	7.2	1036.6	19.1	876.0	16.8	108	100.00	1.44	876.0	7.2
C:\ICPCHEM\1\DATA\cooper\041019\Re110-08.D	10	0.00	56	0.42	0.19628	1.0	2.0329	3.5	0.0751	3.3	0.06457	2.3	1150.9	11.0	1075.5	29.3	929.4	26.1	107	100.00	2.19	929.4	11.0
C:\ICPCHEM\1\DATA\cooper\041019\Re88-06.D	8-	0.00	194	0.92	0.18185	0.8	1.8941	2.0	0.0755	1.8	0.05709	1.3	1076.7	9.6	1028.4	45.8	938.7	43.0	105	100.00	4.08	938.7	9.6
C:\ICPCHEM\1\DATA\cooper\041019\Re72-05.D	2-	0.00	547	0.12	0.17137	0.9	1.7408	1.9	0.0737	1.6	0.06081	2.3	1018.0	8.6	1000.3	12.7	963.9	11.1	102	100.00	2.25	963.9	8.6
C:\ICPCHEM\1\DATA\cooper\041019\Re1-01.D	-0	0.00	235	1.58	0.18341	0.6	1.8733	1.4	0.0741	1.2	0.05577	0.7	1094.0	6.6	1045.1	26.3	968.1	24.8	105	100.00	8.29	968.1	6.6
C:\ICPCHEM\1\DATA\cooper\041019\Re3-01.D	-0	0.00	51	0.53	0.18061	1.3	1.9497	3.3	0.0783	3.0	0.05990	2.2	1066.3	12.8	1032.4	29.0	969.4	26.8	103	100.00	2.01	969.4	12.8
C:\ICPCHEM\1\DATA\cooper\041019\Re25-02.D	5-	0.00	93	0.64	0.17176	0.6	1.7389	1.7	0.0734	1.5	0.05292	0.9	1023.8	6.0	1006.1	19.5	976.3	18.7	102	100.00	1.85	976.3	6.0
C:\ICPCHEM\1\DATA\cooper\041019\Re46-04.D	6-	0.00	32	0.33	0.17746	0.8	1.8122	2.7	0.0741	2.6	0.05645	2.1	1052.5	7.4	1028.3	20.2	981.4	19.0	102	100.00	1.44	981.4	7.4
C:\ICPCHEM\1\DATA\cooper\041019\Re30-02.D	0-	0.00	647	0.09	0.16865	0.4	1.6849	0.9	0.0725	0.8	0.05239	1.1	1004.8	3.7	999.9	6.0	990.2	5.4	100	100.00	1.74	990.2	3.7
C:\ICPCHEM\1\DATA\cooper\041019\Re96-07.D	6-	0.00	465	1.14	0.16737	0.5	1.6654	0.8	0.0722	0.7	0.05049	0.6	1004.8	4.8	997.0	14.1	995.4	13.7	101	100.00	8.64	995.4	4.8
C:\ICPCHEM\1\DATA\cooper\041019\Re54-04.D	4-	0.00	86	0.27	0.19152	0.6	1.9876	1.9	0.0753	1.8	0.06234	2.3	1128.6	6.1	1083.2	15.4	997.9	14.3	104	100.00	1.19	997.9	6.1
C:\ICPCHEM\1\DATA\cooper\041019\Re59-04.D	9-	0.00	208	0.52	0.17110	0.4	1.7225	0.9	0.0730	0.8	0.05206	0.8	1020.7	3.9	1011.9	8.2	999.7	7.7	101	100.00	1.49	999.7	3.9
C:\ICPCHEM\1\DATA\cooper\041019\Re130-09.D	30	0.00	36	0.87	0.19977	1.3	2.0614	5.6	0.0748	5.5	0.06101	2.5	1179.2	14.7	1113.2	50.1	1001.5	46.4	106	100.00	7.16	1001.5	46.4
C:\ICPCHEM\1\DATA\cooper\041019\Re106-08.D	06	0.00	98	0.55	0.17504	0.8	1.7714	2.2	0.0734	2.0	0.05294	1.2	1042.7	7.6	1032.1	16.9	1016.5	16.0	101	100.00	1.55	1016.5	16.0
C:\ICPCHEM\1\DATA\cooper\041019\Re40-03.D	0-	0.00	349	0.62	0.17334	0.4	1.8002	0.9	0.0753	0.8	0.05354	0.8	1032.2	4.1	1026.9	8.5	1023.9	8.0	101	100.00	2.56	1023.9	8.0
C:\ICPCHEM\1\DATA\cooper\041019\Re19-02.D	9-	0.00	277	0.22	0.17504	0.3	1.7764	0.9	0.0736	0.8	0.05331	1.2	1040.7	3.4	1034.7	7.0	1024.6	6.6	101	100.00	1.03	1024.6	6.6
C:\ICPCHEM\1\DATA\cooper\041019\Re86-06.D	6-	0.00	192	0.37	0.17154	0.5	1.7212	1.2	0.0728	1.1	0.05094	0.9	1023.6	4.3	1023.7	8.7	1028.5	8.2	100	100.00	1.33	1028.5	8.2
C:\ICPCHEM\1\DATA\cooper\041019\Re65-05.D	5-	0.00	101	0.16	0.21457	0.7	2.2430	2.9	0.0758	2.8	0.07068	2.6	1251.9	8.1	1173.4	21.5	1034.1	19.6	107	100.00	2.12	1034.1	19.6
C:\ICPCHEM\1\DATA\cooper\041019\Re120-08.D	20	0.00	331	0.41	0.17710	0.4	1.8204	0.8	0.0746	0.7	0.05416	0.7	1052.7	4.0	1045.3	6.7	1035.1	6.0	101	100.00	1.80	1035.1	6.0
C:\ICPCHEM\1\DATA\cooper\041019\Re27-02.D	7-	0.00	270	0.51	0.17050	0.4	1.7332	0.9	0.0737	0.8	0.05147	0.8	1018.0	3.4	1021.4	7.8	1035.3	7.5	100	100.00	1.78	1035.3	7.5
C:\ICPCHEM\1\DATA\cooper\041019\Re73-05.D	3-	0.00	42	0.41	0.17458	1.4	1.8733	5.2	0.0778	5.0	0.05663	2.4	1035.6	13.3	1033.7	38.7	1035.7	37.7	100	100.00	2.45	1035.7	37.7
C:\ICPCHEM\1\DATA\cooper\041019\Re119-08.D	19	0.00	118	0.49	0.19071	0.6	2.0013	1.2	0.0761	1.1	0.05913	1.0	1125.8	6.1	1095.7	11.2	1042.4	10.2	103	100.00	1.22	1042.4	10.2
C:\ICPCHEM\1\DATA\cooper\041019\Re98-07.D	8-	0.00	64	0.32	0.17133	0.8	1.7798	2.2	0.0753	2.0	0.05338	2.0	1019.8	7.8	1025.9	16.3	1042.8	15.5	99	100.00	1.12	1042.8	15.5
C:\ICPCHEM\1\DATA\cooper\041019\Re112-08.D	12	0.00	195	0.63	0.18990	0.5	1.9994	1.2	0.0764	1.1	0.05847	0.8	1122.5	4.9	1095.3	12.1	1049.7	11.4	102	100.00	3.11	1049.7	11.4
C:\ICPCHEM\1\DATA\cooper\041019\Re11-01.D	1-	0.00	211	0.87	0.21638	0.5	2.3726	1.0	0.0795	0.9	0.06729	0.8	1262.6	5.5	1182.5	14.6	1050.7	13.3	107	100.00	4.36	1050.7	13.3
C:\ICPCHEM\1\DATA\cooper\041019\Re63-05.D	3-	0.00	177	0.30	0.18421	0.7	1.9300	1.7	0.0760	1.5	0.05777	1.8	1089.7	7.4	1076.0	13.1	1051.9	12.0	101	100.00	1.52	1051.9	12.0
C:\ICPCHEM\1\DATA\cooper\041019\Re81-06.D	1-	0.00	141	0.82	0.20409	0.6	2.1764	1.3	0.0773	1.2	0.06263	0.9	1199.2	6.7	1144.9	15.4	1053.8	14.1	105	100.00	3.44	1053.8	14.1
C:\ICPCHEM\1\DATA\cooper\041019\Re29-02.D	9-	0.00	250	0.49	0.18057	0.6	1.8239	1.6	0.0733	1.5	0.05324	1.4	1075.6	5.9	1066.0	13.6	1054.8	13.0	101	100.00	1.49	1054.8	13.0
C:\ICPCHEM\1\DATA\cooper\041019\Re70-05.D	0-	0.00	297	0.10	0.17877	0.6	1.8227	1.0	0.0739	0.8	0.05202	1.5	1061.5	5.6	1059.5	9.8	1056.3	9.1	100	100.00	1.21	1056.3	9.1
C:\ICPCHEM\1\DATA\cooper\041019\Re67-05.D	7-	0.00	99	0.57	0.16932	1.1	1.7469	2.5	0.0748	2.2	0.05125	2.3	1012.7	10.7	1023.5	23.0	1056.7	22.2	99	100.00	2.14	1056.7	22.2
C:\ICPCHEM\1\DATA\cooper\041019\Re93-07.D	3-	0.00	96	0.91	0.18083	0.5	1.9557	1.6	0.0784	1.5	0.05594	1.1	1073.7	5.2	1067.2	17.9	1066.7	17.5	101	100.00	4.41	1066.7	17.5
C:\ICPCHEM\1\DATA\cooper\041019\Re115-08.D	15	0.00	462	0.58	0.16997	0.3	1.7335	0.8	0.0740	0.7	0.05066	0.6	1016.5	3.4	1031.1	10.3	1069.5	10.3	99	100.00	2.39	1069.5	10.3
C:\ICPCHEM\1\DATA\cooper\041019\Re121-09.D	21	0.00	316	0.54	0.17220	0.6	1.7420	1.3	0.0734	1.1	0.05070	1.1	1030.3	6.1	1040.4	11.0	1070.4	10.3	99	100.00	1.26	1070.4	10.3
C:\ICPCHEM\1\DATA\cooper\041019\Re129-09.D	29	0.00	122	0.43	0.17460	0.7	1.7611	1.5	0.0732	1.3	0.05094	1.1	1042.1	6.5	1050.0	11.3	1071.5	10.5	99	100.00	1.15	1071.5	10.5
C:\ICPCHEM\1\DATA\cooper\041019\Re21-02.D	1-	0.00	175	0.30	0.20001	0.6	2.1057	1.2	0.0764	1.0	0.06155	1.2	1176.2	7.0	1141.4	9.6	1079.7	8.2	103	100.00	1.58	1079.7	8.2
C:\ICPCHEM\1\DATA\cooper\041019\Re104-07.D	04	0.00	88	0.72	0.18623	0.7	2.0734	1.7	0.0807	1.5	0.05899	1.4	1099.6	7.5	1093.6	26.9	1090.7	26.3	101	100.00	2.10	1090.7	26.3
C:\ICPCHEM\1\DATA\cooper\041019\Re9-01.D	-0	0.00	168	0.47	0.19220	0.6	2.0951	1.3	0.0791	1.2	0.06059	1.1	1132.9	6.0	1117.6	11.8	1094.5	11.0	101	100.00	1.07	1094.5	11.0
C:\ICPCHEM\1\DATA\cooper\041019\Re77-06.D	7-	0.00	114	0.55	0.17958	0.6	1.9226	1.7	0.0776	1.6	0.05533	1.8	1066.1	6.2	1074.6	16.0	1098.3	15.6	99	100.00	1.80	1098.3	15.6

C:\ICPCHEM\1\DATA\cooper\041019\Re132-09.D	32	0.00	206	0.20	0.17979	0.7	1.9179	1.3	0.0774	1.1	0.05676	1.4	1065.8	7.3	1076.4	9.3	1100.5	8.0	99	100.00	1.26	1100.5	8.0
C:\ICPCHEM\1\DATA\cooper\041019\Re60-04.D	0-	0.00	149	1.26	0.21737	0.8	2.3514	1.8	0.0785	1.6	0.06548	1.0	1273.3	11.0	1211.0	47.7	1114.9	45.1	105	100.00	3.53	1114.9	45.1
C:\ICPCHEM\1\DATA\cooper\041019\Re130-09.D	30	0.00	29	0.87	0.19393	0.9	2.2919	3.8	0.0857	3.7	0.06255	2.2	1138.0	10.2	1127.8	37.4	1119.9	36.7	101	100.00	4.74	1119.9	36.7
C:\ICPCHEM\1\DATA\cooper\041019\Re56-04.D	6-	0.00	180	0.81	0.19545	0.7	2.0382	1.6	0.0756	1.4	0.05783	0.8	1156.9	7.6	1142.2	25.0	1122.8	24.3	101	100.00	2.22	1122.8	24.3
C:\ICPCHEM\1\DATA\cooper\041019\Re78-06.D	8-	0.00	163	0.29	0.18843	0.5	1.9799	1.2	0.0762	1.1	0.05505	1.3	1115.6	5.0	1118.0	11.0	1125.6	10.6	100	100.00	1.44	1125.6	10.6
C:\ICPCHEM\1\DATA\cooper\041019\Re128-09.D	28	0.00	199	0.28	0.22699	0.6	2.4995	1.1	0.0799	0.9	0.07084	1.3	1318.5	7.7	1254.7	9.4	1150.5	7.8	105	100.00	1.61	1150.5	7.8
C:\ICPCHEM\1\DATA\cooper\041019\Re26-02.D	6-	0.00	613	0.45	0.18244	0.5	1.9316	0.8	0.0768	0.6	0.05586	1.3	1084.9	7.8	1106.5	43.2	1154.9	43.9	98	100.00	3.61	1154.9	43.9
C:\ICPCHEM\1\DATA\cooper\041019\Re100-07.D	00	0.00	180	0.55	0.19651	0.5	2.1251	1.1	0.0784	1.0	0.05859	0.8	1160.5	5.1	1159.9	9.2	1165.6	8.6	100	100.00	1.87	1165.6	8.6
C:\ICPCHEM\1\DATA\cooper\041019\Re42-03.D	2-	0.00	302	0.35	0.19714	0.4	2.1717	0.8	0.0799	0.7	0.06044	0.9	1160.8	4.3	1162.0	7.1	1168.2	6.6	100	100.00	1.34	1168.2	6.6
C:\ICPCHEM\1\DATA\cooper\041019\Re76-06.D	6-	0.00	28	0.52	0.21421	0.8	2.3933	2.5	0.0810	2.4	0.06578	1.7	1252.1	9.0	1219.6	23.0	1169.2	21.8	103	100.00	1.45	1169.2	21.8
C:\ICPCHEM\1\DATA\cooper\041019\Re64-05.D	4-	0.00	42	0.90	0.22887	0.9	2.4759	2.8	0.0785	2.7	0.06790	1.5	1337.8	11.3	1269.5	33.9	1170.0	31.8	105	100.00	2.59	1170.0	31.8
C:\ICPCHEM\1\DATA\cooper\041019\Re122-09.D	22	0.00	49	1.30	0.19418	1.1	2.5387	3.4	0.0948	3.2	0.06319	2.2	1134.0	12.2	1141.9	46.2	1174.7	46.2	99	100.00	4.88	1174.7	46.2
C:\ICPCHEM\1\DATA\cooper\041019\Re61-05.D	1-	0.00	381	0.42	0.18641	0.6	1.8822	1.2	0.0732	1.1	0.04955	1.0	1111.9	5.8	1132.6	10.9	1178.0	10.4	98	100.00	1.97	1178.0	10.4
C:\ICPCHEM\1\DATA\cooper\041019\Re33-03.D	3-	0.00	218	1.20	0.18747	0.5	1.9645	1.1	0.0760	1.0	0.05501	0.5	1120.1	5.5	1139.4	22.2	1191.6	22.4	98	100.00	2.74	1191.6	22.4
C:\ICPCHEM\1\DATA\cooper\041019\Re8-01.D	-0	0.00	317	1.33	0.21514	0.4	2.5372	1.0	0.0855	0.9	0.06601	0.7	1259.6	5.1	1230.2	14.8	1197.7	14.3	102	100.00	7.81	1197.7	14.3
C:\ICPCHEM\1\DATA\cooper\041019\Re28-02.D	8-	0.00	106	0.44	0.21234	0.5	2.3898	1.2	0.0816	1.1	0.06413	1.1	1243.5	5.6	1232.4	10.6	1218.7	10.0	101	100.00	1.17	1218.7	10.0
C:\ICPCHEM\1\DATA\cooper\041019\Re125-09.D	25	0.00	124	0.87	0.19423	0.5	2.0979	1.5	0.0783	1.5	0.05687	0.7	1153.2	5.0	1173.6	14.3	1222.1	14.2	98	100.00	1.85	1222.1	14.2
C:\ICPCHEM\1\DATA\cooper\041019\Re103-07.D	03	0.00	82	0.35	0.17845	0.8	2.3217	4.4	0.0944	4.3	0.06831	4.4	1045.3	9.3	1104.0	50.0	1225.6	52.4	95	100.00	2.65	1225.6	52.4
C:\ICPCHEM\1\DATA\cooper\041019\Re95-07.D	5-	0.00	578	0.44	0.17679	0.4	1.8602	0.8	0.0763	0.7	0.04851	1.0	1057.0	4.4	1114.5	7.3	1232.0	6.9	95	100.00	2.09	1232.0	6.9
C:\ICPCHEM\1\DATA\cooper\041019\Re44-03.D	4-	0.00	81	0.70	0.21143	0.5	2.3542	1.3	0.0808	1.2	0.06225	1.1	1243.0	6.3	1240.8	18.0	1245.5	17.5	100	100.00	1.61	1245.5	17.5
C:\ICPCHEM\1\DATA\cooper\041019\Re35-03.D	5-	0.00	73	0.48	0.22021	0.6	2.5766	1.9	0.0849	1.8	0.06777	1.2	1284.0	7.0	1274.3	16.4	1264.4	15.8	101	100.00	1.14	1264.4	15.8
C:\ICPCHEM\1\DATA\cooper\041019\Re69-05.D	9-	0.00	116	0.35	0.23317	0.7	2.8014	1.6	0.0871	1.5	0.07543	1.1	1347.8	8.2	1318.1	14.6	1273.7	13.5	102	100.00	2.00	1273.7	13.5
C:\ICPCHEM\1\DATA\cooper\041019\Re6-01.D	-0	0.00	210	0.36	0.16843	0.8	1.8643	1.8	0.0803	1.6	0.04438	1.4	1011.2	7.6	1118.3	12.6	1336.0	12.5	90	100.00	1.01	1336.0	12.5
C:\ICPCHEM\1\DATA\cooper\041019\Re57-04.D	7-	0.00	160	0.63	0.23431	0.7	2.7707	1.5	0.0858	1.3	0.06915	1.2	1363.0	8.6	1350.9	14.6	1340.5	13.6	101	100.00	3.04	1340.5	13.6
C:\ICPCHEM\1\DATA\cooper\041019\Re38-03.D	8-	0.00	115	0.47	0.17711	0.7	2.5911	1.8	0.1061	1.7	0.07037	1.5	1033.7	7.0	1143.6	18.4	1366.9	19.4	90	100.00	2.19	1366.9	19.4
C:\ICPCHEM\1\DATA\cooper\041019\Re66-05.D	6-	0.00	182	0.48	0.25016	0.5	3.0872	1.1	0.0895	1.0	0.07452	0.8	1441.7	6.6	1424.0	10.2	1402.4	9.3	101	100.00	1.06	1402.4	9.3
C:\ICPCHEM\1\DATA\cooper\041019\Re111-08.D	11	0.00	41	0.43	0.21012	0.6	2.4195	1.9	0.0835	1.8	0.05620	1.6	1238.9	6.8	1301.4	15.2	1409.3	15.1	95	100.00	1.40	1409.3	15.1
C:\ICPCHEM\1\DATA\cooper\041019\Re114-08.D	14	0.00	134	0.46	0.24074	0.5	2.9944	1.0	0.0902	0.9	0.07221	0.9	1392.8	5.9	1398.7	9.0	1412.9	8.3	100	100.00	1.34	1412.9	8.3
C:\ICPCHEM\1\DATA\cooper\041019\Re20-02.D	0-	0.00	217	1.20	0.24690	0.4	3.0390	0.8	0.0893	0.7	0.07263	0.6	1433.6	5.3	1423.4	18.2	1423.4	17.9	101	100.00	5.30	1423.4	17.9
C:\ICPCHEM\1\DATA\cooper\041019\Re22-02.D	2-	0.00	83	2.36	0.23283	0.5	3.0513	1.6	0.0950	1.5	0.06990	0.8	1365.0	7.5	1375.9	33.8	1428.2	34.0	99	100.00	12.37	1428.2	34.0
C:\ICPCHEM\1\DATA\cooper\041019\Re24-02.D	4-	0.00	153	0.80	0.26545	0.5	3.3560	0.9	0.0917	0.7	0.07886	0.7	1522.6	6.3	1482.8	10.2	1436.0	9.4	103	100.00	1.61	1436.0	9.4
C:\ICPCHEM\1\DATA\cooper\041019\Re91-07.D	1-	0.00	135	1.16	0.22225	0.9	2.5909	2.1	0.0846	1.8	0.06310	1.0	1315.2	11.2	1364.6	20.6	1461.5	20.0	96	100.00	2.17	1461.5	20.0
C:\ICPCHEM\1\DATA\cooper\041019\Re52-04.D	2-	0.00	122	0.49	0.24770	0.6	3.1721	1.3	0.0929	1.2	0.07325	1.4	1430.2	7.5	1449.3	13.1	1483.0	12.4	99	100.00	2.52	1483.0	12.4
C:\ICPCHEM\1\DATA\cooper\041019\Re36-03.D	6-	0.00	83	0.60	0.24435	0.8	3.2233	2.3	0.0957	2.2	0.07320	1.7	1413.6	10.6	1453.2	21.6	1520.4	21.0	97	100.00	1.77	1520.4	21.0
C:\ICPCHEM\1\DATA\cooper\041019\Re23-02.D	3-	0.00	256	0.96	0.21404	0.7	2.6978	1.3	0.0914	1.1	0.05914	1.5	1268.7	9.0	1407.9	26.4	1635.3	27.3	90	100.00	2.07	1635.3	27.3
C:\ICPCHEM\1\DATA\cooper\041019\Re79-06.D	9-	0.00	16	1.92	0.32974	1.1	5.1955	2.7	0.1143	2.4	0.09873	1.1	1842.0	20.2	1753.7	55.7	1679.2	53.8	105	100.00	5.77	1679.2	53.8
C:\ICPCHEM\1\DATA\cooper\041019\Re74-05.D	4-	0.00	419	0.52	0.29559	0.7	4.4308	1.4	0.1087	1.1	0.09306	1.5	1665.0	11.1	1673.8	16.2	1690.0	15.0	99	100.00	1.74	1690.0	15.0
C:\ICPCHEM\1\DATA\cooper\041019\Re1045-07.D	04	0.00	159	0.88	0.29441	0.4	4.2290	0.8	0.1042	0.6	0.08589	0.6	1671.3	6.2	1678.1	9.9	1696.7	9.3	100	100.00	2.10	1696.7	9.3
C:\ICPCHEM\1\DATA\cooper\041019\Re10-01.D	0-	0.00	110	1.11	0.30712	0.8	4.6490	1.9	0.1098	1.7	0.09224	1.3	1733.2	13.1	1714.1	25.9	1709.6	24.8	101	100.00	3.23	1709.6	24.8
C:\ICPCHEM\1\DATA\cooper\041019\Re123-09.D	23	0.00	145	0.40	0.29262	0.5	4.4792	0.9	0.1110	0.8	0.09324	0.9	1650.3	7.3	1689.3	13.8	1742.0	13.3	98	100.00	0.96	1742.0	13.3
C:\ICPCHEM\1\DATA\cooper\041019\Re18-02.D	8-	0.00	106	1.27	0.30475	0.7	5.3793	1.7	0.1280	1.5	0.09945	1.2	1690.6	11.4	1709.3	26.0	1747.3	25.5	99	100.00	4.58	1747.3	25.5
C:\ICPCHEM\1\DATA\cooper\041019\Re68-05.D	8-	0.00	105	1.36	0.32745	0.6	4.8650	1.3	0.1078	1.2	0.09461	0.9	1836.9	10.7	1794.5	24.7	1758.5	23.9	102	100.00	4.03	1758.5	23.9
C:\ICPCHEM\1\DATA\cooper\041019\Re15-01.D	5-	0.00	185	0.85	0.30328	0.5	4.5600	1.1	0.1090	1.0	0.08828	0.8	1714.8	7.6	1740.2	12.2	1780.1	11.5	99	100.00	3.61	1780.1	11.5
C:\ICPCHEM\1\DATA\cooper\041019\Re12-01.D	2-	0.00	158	1.17	0.29159	0.4	4.1927	0.8	0.1043	0.7	0.08245	0.6	1668.1	7.0	1713.7	17.4	1783.3	17.2	97	100.00	3.11	1783.3	17.2
C:\ICPCHEM\1\DATA\cooper\041019\Re82-06.D	2-	0.00	85	0.94	0.34076	0.6	5.4864	1.1	0.1168	0.9	0.10395	0.7	1885.6	10.7	1836.0	14.3	1790.1	13.0	103	100.00	2.33	1790.1	13.0
C:\ICPCHEM\1\DATA\cooper\041019\Re43-03.D	3-	0.00	176	0.95	0.33686	0.6	5.1393	1.0	0.1107	0.8	0.09721	0.8	1880.4	9.7	1839.4	14.6	1804.0	13.5	102	100.00	3.12	1804.0	13.5
C:\ICPCHEM\1\DATA\cooper\041019\Re17-02.D	7-	0.00	63	1.02	0.33218	0.5	5.2236	1.2	0.1140	1.1	0.09652	0.7	1857.3	8.1	1847.7	13.5	1848.4	12.8	101	100.00	2.18	1848.4	12.8
C:\ICPCHEM\1\DATA\cooper\041019\Re41-03.D	1-	0.00	97	0.98	0.32302	0.4	5.0239	1.1	0.1128	1.0	0.09303	1.0	1814.9	7.3	1827.5	14.5	1852.8	14.0	99	100.00	3.15	1852.8	14.0
C:\ICPCHEM\1\DATA\cooper\041019\Re37-03.D	7-	0.00	62	1.82	0.33397	0.5	5.2425	1.5	0.1138	1.4	0.09557	0.8	1879.2	9.7	1873.9	23.4	1888.6	22.8	100	100.00	5.74	1888.6	22.8
C:\ICPCHEM\1\DATA\cooper\041019\Re126-09.D	26	0.00	103	1.17	0.31428	0.4	5.0388	0.9	0.1163	0.8	0.09132	0.7	1771.9	7.2	1821.5	13.8	1891.5	13.4	97	100.00	2.22	1891.5	13.4
C:\ICPCHEM\1\DATA\cooper\041019\Re118-08.D	18	0.00	291	0.74	0.30898	0.5	4.9499	0.7	0.1162	0.5	0.08487	0.7	1750.6	8.3	1850.2	7.3	1971.6	5.8	95	100.00	1.78	1971.6	5.8
C:\ICPCHEM\1\DATA\cooper\041019\Re32-03.D	2-	0.00	384	0.62	0.36960	0.3	6.3297	0.6	0.1242	0.5	0.10678	0.7	2031.8	5.7	2015.6	6.4	2005.2	5.7	101	100.00	2.57	2005.2	5.7
C:\ICPCHEM\1\DATA\cooper\041019\Re90-06.D	0-	0.00	243	0.63	0.34772	0.3	5.8966	0.7	0.1230	0.6	0.09897	0.7	1930.8	5.9	1965.9	7.6	2009.2	7.0	98	100.00	2.13	2009.2	7.0
C:\ICPCHEM\1\DATA\cooper\041019\Re62-05.D	2-	0.00	540	0.22	0.46911	0.4	10.4917	0.6	0.1622	0.4	0.13086	0.7	2481.8	8.7	2478.8	5.3	2478.2	3.5	100	100.00	2.11	2478.2	3.5
C:\ICPCHEM\1\DATA\cooper\041019\Re34-03.D	4-	0.00	201	1.35	0.43563	0.5	9.5295	1.3	0.1587	1.2	0.11881	1.7	2361.6	11.0	2422.7	18.4	2491.5	17.7	97	100.00	3.70	2491.5	17.7
C:\ICPCHEM\1\DATA\cooper\041019\Re116-08.D	16	0.00	69	0.67	0.61806	0.5	21.8208	0.8	0.2561	0.6	0.16910	1.4	3107.4	13.3	3171.1	9.9	3216.7	8.4	98	100.00	2.06	3216.7	8.4

Appendix C: Rock Sample List

			GPS Location				
Field Site	Sample #	UC #	East	South	Formation	Hand Specimen	Thin Section
Nibelungen Valley	T1	18938	E161°27.318'	S77°35.814'	New Mountain Sandstone Formation	Y	Y
Nibelungen Valley	T2	18939			Below Heimdall ES, New Mountain Formation	Y	Y
Nibelungen Valley	T3	18940			New Mountain Sst	Y	Y
Nibelungen Valley	T4	18941	E161°26.672'	S77°35.918'	On Heimdall ES, Odin Arkose Member, Altar Mountian Formation	Y	Y
Nibelungen Valley	T5	18942			upper Windy Gully Sst Formation	Y	Y
Nibelungen Valley	T6	18943			Terra Cotta Siltstone	Y	
Nibelungen Valley	T7	18944			Terra Cotta Siltstone	Y	
Nibelungen Valley	T8	18945			Upper New Mountain Sst Fmtn	Y	
Nibelungen Valley	T9	18946	E161°19.611'	S77°35.432'	New Mountain Sst	Y	Y
Nibelungen Valley	T10	18947	E161°19.611'	S77°35.432'	New Mountain Sst	Y	
Nibelungen Valley	T11	18948			New Mountain Sst	Y	
Nibelungen Valley	T12	18949			On Heimdall ES, Odin Arkose Member, Altar Mountian Formation	Y	Y
Nibelungen Valley	T13	18950	E161°20.179'	S77°36.645'	Kukri ES, Windy Gully Basal Conglomerate	Y	
Nibelungen Valley	T14	18951			lower Windy Gully Sst Formation	Y	
Nibelungen Valley	T15	18952			Terra Cotta Siltstone	Y	Y
Nibelungen Valley	T16	18953			Lower New Mountain Sst Formation	Y	
Nibelungen Valley	T17	18954			Terra Cotta Siltstone	Y	
Nibelungen Valley	T18	18955	E161°17.363'	S77°36.796'	On Heimdall ES, Odin Arkose Member, Altar Mountian Formation	Y	
Nibelungen Valley	T19	18956			Lower New Mountain Sst Formation	Y	
Nibelungen Valley	T20	18957	E161°30.573'	S77°34.783'	Windy Gully Sandstone	Y	
Nibelungen Valley	T21	18958			Windy Gully Sandstone	Y	
Nibelungen Valley	T22	18959			Windy Gully Sandstone (Basal Conglomerate)	Y	Y
Nibelungen Valley	T23	18960			Windy Gully Sandstone	Y	
Nibelungen Valley	T24	18961			Terra Cotta Siltstone	Y	
Nibelungen Valley	T26	18963			Windy Gully Sandstone (Basal Conglomerate)	Y	
Nibelungen Valley	T27	18964			Windy Gully Sandstone (Basal Conglomerate)	Y	
Nibelungen Valley	T30	18967			Lower Windy Gully Sst	Y	
Nibelungen Valley	T31	18968	E160°57.550'	S77°35.263'	On Heimdall ES, Odin Arkose Member, Altar Mountian Formation	Y	Y
Folkvanger Valley	T32	18969			Odin Arkose, Altar MtnFormation	Y	
Folkvanger Valley	T33	18970			Lower New Mountain Sst Formation	Y	
Folkvanger Valley	T34	18971			Lower New Mountain Sst Formation	Y	Y
Folkvanger Valley	T35	18972			Lower New Mountain Sst Formation	Y	
Folkvanger Valley	T36	18973			New Mountain Sandstone Formation	Y	
Folkvanger Valley	T37	18974			New Mountain Sandstone Formation	Y	
Folkvanger Valley	T38	18975			New Mountain Sandstone Formation	Y	
Folkvanger Valley	T39	18976			New Mountain Sandstone Formation	Y	Y
Folkvanger Valley	T39A	18977	E160°57.660'	S77°35.573'	New Mountain Sandstone Formation	Y	
Folkvanger Valley	T40	18978			Windy Gully Sandstone (Basal Conglomerate)	Y	
Folkvanger Valley	T41	18979			Windy Gully Sandstone (Basal Conglomerate)	Y	Y
Folkvanger Valley	T42	18980			Lower Windy Gully Sandstone Formation	Y	Y
Folkvanger Valley	T43	18981			Lower Windy Gully Sandstone Formation	Y	
Folkvanger Valley	T44	18982	E161°05.230'	S77°35.395'	On Heimdall ES, Odin Arkose Member, Altar Mountian Formation	Y	Y
Folkvanger Valley	T45	18983			Windy Gully Sandstone (Basal Conglomerate)	Y	Y
Knobhead (Handsley Valley)	T50	18988			New Mountain Sandstone Formation	Y	
Knobhead (Handsley Valley)	T51	18989			New Mountain Sandstone Formation	Y	
Knobhead (Handsley Valley)	T52	18990			Odin Arkose Member, Altar Mountain	Y	
Knobhead (Handsley Valley)	T53	18991			Top of Odin Arkose Member	Y	
Knobhead (Handsley Valley)	T54	18992			Windy Gully Sandstone Formation	Y	
Knobhead (Handsley Valley)	T55	18993			On Heimdall ES, Odin Arkose Member, Altar Mountian Formation	Y	
Knobhead (Handsley Valley)	T56	18994			Lower New Mountain Sst Formation	Y	
Knobhead (Handsley Valley)	T57	18995			On Heimdall ES, Odin Arkose Member, Altar Mountian Formation	Y	
Knobhead (Handsley Valley)	T58	18996			Terra Cotta Siltstone	Y	
Knobhead (Handsley Valley)	T59	18997			Terra Cotta Siltstone	Y	
Knobhead (Handsley Valley)	T60	18998			Terra Cotta Siltstone	Y	
Knobhead (Handsley Valley)	T61	18999			Upper New Mountain Sst Formation	Y	Y
Knobhead (Handsley Valley)	T62	19000			Terra Cotta Siltstone	Y	Y
Knobhead (Handsley Valley)	T63	19001			New Mountain Sandstone Formation	Y	Y
Knobhead (Handsley Valley)	T64	19002			New Mountain Sandstone Formation	Y	
Knobhead (Handsley Valley)	T65	19003			On Heimdall ES, Odin Arkose Member, Altar Mountian Formation	Y	
Knobhead (Handsley Valley)	T66	19004			Terra Cotta Siltstone	Y	
New Mountain (Windy Gully)	T67	19005			Basement	Y	
New Mountain (Windy Gully)	T68	19006			Windy gully Basal Cconglomerate	Y	
New Mountain (Windy Gully)	T69	19007			Windy gully Basal Cconglomerate	Y	
New Mountain (Windy Gully)	T70	19008			Windy Gully Basal Conglomerate	Y	
New Mountain (Windy Gully)	T71	19009			New Mountain Sandstone Formation	Y	
New Mountain (Windy Gully)	T73	19011			Heimdall ES	Y	
Rotunda	T80	19012			New Mountain Sandstone Formation	Y	
Rotunda	T81	19013			New Mountain Sandstone Formation	Y	
Rotunda	T82	19014			New Mountain Sandstone Formation	Y	
Rotunda	T83	19015			Odin Arkose, Altar Mtn Formation	Y	
Rotunda	T84	19016			Odin Arkose, Altar Mtn Formation	Y	
Rotunda	T85	19017			Odin Arkose, Altar Mtn Formation	Y	